PAN
ARCHIVES OF ACOUSTICS
Vol. **37**, No. 4, pp. 499–514 (2012)

DOI: 10.2478/v10168-012-0062-z

Analysis of the Grid Sampling Method for Noise Mapping

Valentín GÓMEZ ESCOBAR, Juan Miguel BARRIGÓN MORILLAS, Guillermo REY GOZALO, Rosendo VÍLCHEZ-GÓMEZ, Javier CARMONA del RÍO, Juan A. MÉNDEZ SIERRA

Departamento de Física Aplicada, E. Politécnica, Universidad de Extremadura
Avda. de la Universidad s/n, 10003 Cáceres, Spain; e-mail: valentin@unex.es

(*received September 19, 2011; accepted October 10, 2012*)

The grid method is the most widely used technique for measurement-based noise assessment, and indeed is part of the ISO 1996-2 standard. Nevertheless it has certain disadvantages. The present work is an analysis of the grid method for evaluating noise, firstly in the city of Cáceres and, secondly in two other smaller towns. Using as reference a 200 metre grid study, a study was made of the effect of varying the size and form of the grid on the city's overall noise value, the percentage of data found to lie above some reference thresholds, and the noise value assigned to a certain zone of the city. The ISO 1996 recommendations of the necessity of new sampling points and the method's predictive capacity for these new measurements were also analyzed.

Keywords: grid method, noise mapping, urban noise.
PACS numbers: 43.50.Yw, 43.50.Rq.

1. Introduction

With the rapid growth of cities in the last few decades, noise has become one of the major concerns of citizens, and its evaluation and control is now an integral part of the responsibilities of the public authorities of developing countries (COM, 2002).

Different methods have been proposed for selecting sampling points in measurement-based noise assessment [Brown, Lam (1987) give an extensive review]. Of these, the grid method has long been the most commonly used. Indeed, it is part of the ISO 1996-2 standard in both the old (ISO 1996-2, 1987) and the revised (ISO 1996-2, 2007) versions. It has certain disadvantages, however, so that a number of alternative methods have been proposed (Glaser, Silver, 1979; Broderson *et al.*, 1981; Chakrabarty *et al.*, 1997; Piccolo *et al.*, 2005; Barrigón *et al.*, 2005; 2010; Romeu *et al.*, 2006), but none of them have as yet achieved generalized acceptance.

Basically, the grid method consists of superposing a certain grid over the map of a city. The nodes of the grid are then taken to be the sampling points, although sometimes only some of the nodes are chosen. The elements of the grid are generally squares, but other polygons may be used. The grid size can be regular or may vary from one zone of the city to another. Indeed, when a greater than 5 decibel difference is measured between two adjacent points, according to ISO 1996-2 (ISO 1996-2, 1987; ISO 1996-2, 2007) an additional sampling point should be measured between these two points. Various studies using this method are reviewed by Brown and Lam (1987), and more recent applications can be found elsewhere (Zannin *et al.*, 2002; Sommerhoff *et al.*, 2004; Martín *et al.*, 2006).

The present work studies the grid method for the evaluation of urban noise. For this purpose, in the city of Cáceres [a medium-sized town (about 95 000 inhabitants) located in the southwest of Spain], an initial 200 metre grid (involving 645 measurements) was used as reference, and then, with the same measurements, an analysis was made of the effect of increasing the grid size or of rotating the grid. In the same way, we studied the ISO 1996 recommendations for the necessity of new sampling points, and the method's predictive capacity by using grid sizes larger than 200 metres to "predict" the known values at points inside the squares of that grid. Some of the studies carried out in the city of Cáceres were also applied in two smaller towns (Don Benito and Olivenza), in order to corroborate the results obtained in Cáceres.

In sum, the goals of the present work were:

1. To study the procedure's capacity to provide an overall evaluation of noise in a town.

2. To evaluate the influence of varying the grid size on the noise value associated with a given zone of the town.
3. To analyze the ISO 1996-2 recommendation with respect to the need for new measurements.
4. To study the method's capacity to predict the noise value of new measurements.

The work is structured as follows. Section 2 describes the towns, and the methods used for the sampling point selection, for the noise measurements, and for the statistical analysis. Section 3 presents the results, and Sec. 4 the conclusions.

2. Methods

2.1. The towns studied

The city of Cáceres has a population of about 95 000 inhabitants (increasing to over 110 000 during the teaching period due to the influx of more than 10 000 students at the University of Extremadura and an important number of tourists). It is the second largest town of Extremadura (region located in the southwest of Spain). The old part of the town centre (it is a UNESCO World Heritage site) is characterized by pedestrian streets (except that reduced traffic is allowed in some of them). The desire to conserve this old part of the town and the differences in altitude of the various parts of the town have been the major factors influencing urban development in general, and the width and conformation of almost all the city streets in particular. In recent years, the construction of a ring-road around the town has changed its traffic patterns, greatly reducing the number of heavy vehicles and, to a lesser extent, other vehicles that pass through the town. Industrial activities are of minor relevance, and are concentrated mainly in the outskirts, outside the study area (shown in Figs. 1 to 3). The mean annual temperature and rainfall are 16.1°C and 523 mm, respectively.

The town of Don Benito has a population of about 35 000 inhabitants and is the fifth largest town of Extremadura. It has no historical part, and is located in a flat region near the River Guadiana.

The town of Olivenza has a population of about 10 000 inhabitants and is located very close to Portugal (indeed Olivenza belonged to Portugal from 1297 to 1801). It has a walled old part, and most of it streets are paved with stones of a narrow U-shaped cross-section.

2.2. Selection of sampling points for the noise map grids studied

2.2.1. The city of Cáceres

To apply the grid method to the city of Cáceres, the area of the city (approximately 10 km^2) made it possible to select a fairly small grid size as reference. In particular, for the sampling point selection a 200 m resolution square grid was drawn on the town map. A similar grid size has been used in previous studies (García *et al.*, 1990; Sanchís *et al.*, 2000; Barrigón Morillas *et al.*, 2002), although coarser grids are usually employed (Sommerhoff *et al.*, 2004; Martín *et al.*, 2006; etc.).

The nodes of this grid were selected as the measurement points. When a point was inaccessible, the nearest accessible point was selected. With this grid size, there were a total of 215 measurement points, forming 168 squares. Squares corresponding to industrial zones were not considered. Figure 1 shows the map of Cáceres with this 200 metre size grid that served as the reference for the study.

These 215 measurement points were used for a first analysis of the 200 metre grid. Then the same measurements were used to compute noise maps with coarser grid sizes in which no new measurements were necessary. The different grid sizes studied were:

a. the initial 200 m grid size,
b. two different placements of a 283 m grid size (obtained by rotating 45° the initial 200 m grid) (shown in Fig. 2),
c. four different alternatives of the 400 m grid size (two of them shown in Figs. 3a,b),
d. nine different alternatives of the 600 m grid size (one of them shown in Fig. 3c),
e. four different alternatives of the 800 m grid size. Although there are twelve possible alternatives, only the four that would involve more than 10 sampling points were selected. One of these alternatives is shown in Fig. 3d.

Information about the number of measurement points and the number of grid squares of each alternative analyzed is provided in Table 1.

2.2.2. The other towns studied

In the towns of Don Benito and Olivenza (with areas of 7.5 km^2 and 2 km^2, respectively) the same grid resolution as in Cáceres was used in order to allow comparisons. In these towns the different grid sizes studied were:

a. the initial 200 m grid size,
b. the two different placements of a 283 m grid size, and
c. the four different alternatives of the 400 m grid size.

Information about the number of measurement points and the number of grid squares of each alternative analyzed is provided in Table 7.

Fig. 1. City map and sampling points of Cáceres with the 200 m size grid used as reference superposed.

Fig. 2. City map and sampling points of Cáceres. The two alternatives of the 283 m (200 m rotated) size grid used.

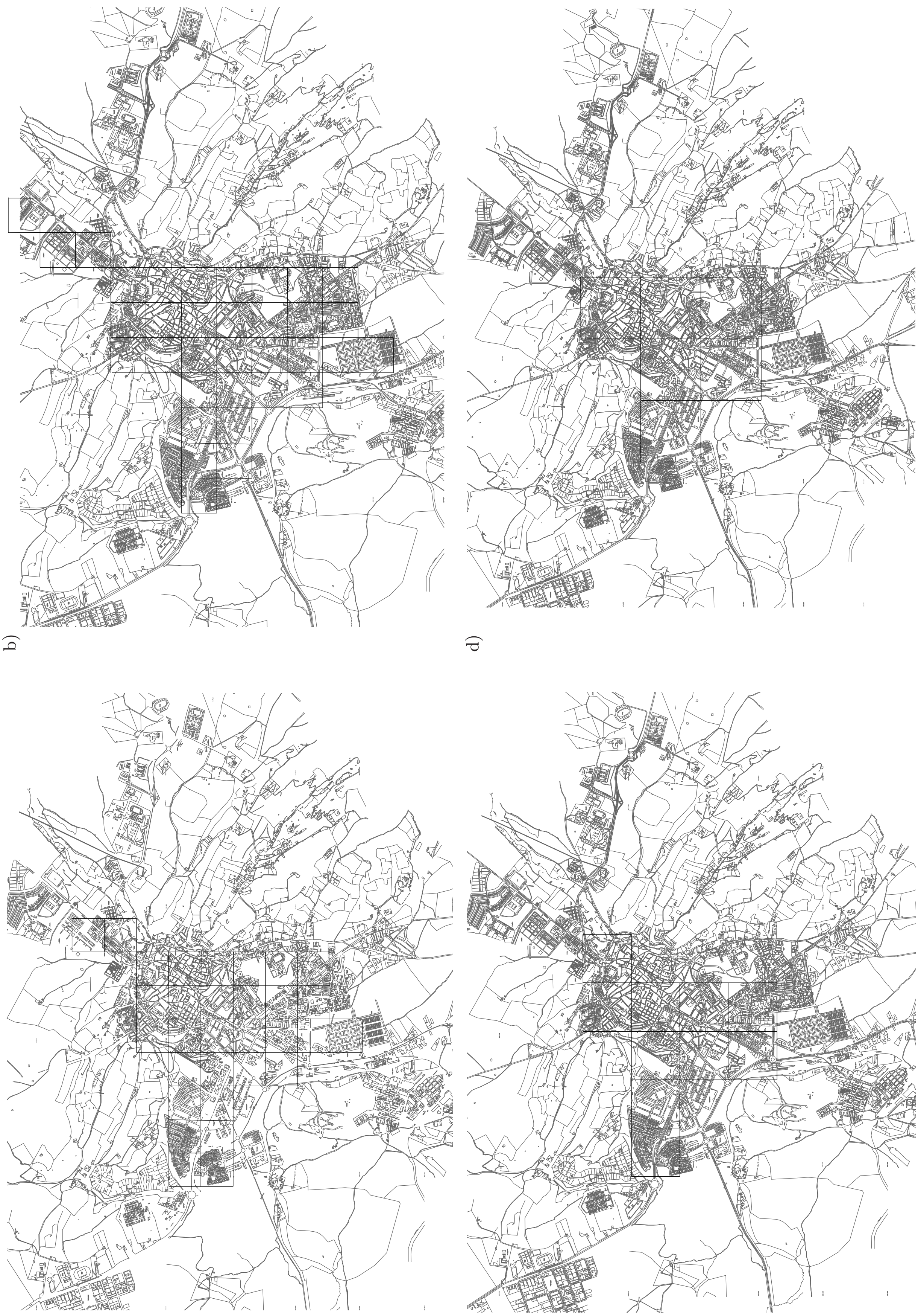

Fig. 3. City map and sampling points of Cáceres. Two of the alternatives of the 400 m size grid used (a) and (b). One of the alternatives of the 600 m size grid studied (c). One of the alternatives of the 800 m size grid studied (d).

Table 1. Grid size, measurement points, number of measurements, grid squares, new necessary points according to ISO 1996-2 recommendations, and percentage represented by these new necessary points with respect to the measurement points employed for the different alternatives of each grid method analyzed. I: grid of 200 metres; II–III: 45°-rotated 200 metre grid (grid of 283 metres) (two alternatives); IV–VII: 400 metre grid (four alternatives); VIII–XVI: 600 metre grid (nine alternatives); XVII–XX: 800 metre grid (four alternatives).

	Alternative																			
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX
Grid size (metres)	200	283	283	400	400	400	400	600	600	600	600	600	600	600	600	600	800	800	800	800
Measurement points	215	102	104	53	55	48	49	23	20	21	17	18	18	19	19	19	12	11	11	13
Measurements	645	306	312	153	165	144	147	64	60	63	51	54	54	57	57	57	36	33	33	39
Grid squares	168	71	71	32	34	29	29	10	10	10	8	9	9	10	10	10	5	5	4	6
Minimum additional new necessary points	185	100	99	42	53	46	49	20	20	17	17	12	13	18	16	17	6	10	11	10
Minimum additional new necessary points (%)	86	98	95	79	96	96	100	87	100	81	100	67	76	95	84	89	50	91	100	77

2.3. Measurement procedure

All the measurements were made in the period from 8 a.m. to 8 p.m. (working hours). The measurements were made on different days of the week (only working days were studied) and at different time-intervals of the day looking for an uniform distribution along the whole temporal period. To this effect, at each sampling point, in Olivenza and Cáceres, three measurements were made in three different time-intervals randomly selected from the following four: [8 a.m.–11 a.m.; 11 a.m.–14 p.m.; 14 p.m.–17 p.m.; 17 p.m.–20 p.m.]. In Don Benito, measurements were carried out in the four time intervals. Fifteen minute samples were used for each measurement.

Measurements in Cáceres were carried out by two people during the months of April and May of the year 2005 (8 weeks) following the ISO 1996-2 (ISO 1996-2, 1987) guidelines, using a 2238 Brüel & Kjaer type-I sound-level meter, with tripod and windshield. Calibration was performed using a 4231 Brüel & Kjaer calibrator. In Don Benito and Olivenza, the measurements were made by one person with the same equipment in the years 2005 (4 weeks also during the months of April and May) and 2007 (3 weeks during the months of March and April), respectively. The measurement days corresponded to the typical continental climate of spring when the weather conditions were convenient (no rain or wet roads, and light winds).

The measurement points were located at the vertices of the cells or, when these were inaccessible, at the nearest location. This nearest location was looked for by making concentric circles with an increasing radius, until finding an appropriate sampling location. The placement of the sound level meter was similar for all the sampling points near a street – approximately one meter from the curb, oriented to the centre or the road and far enough to any reflecting surface. The sampling selection procedure implied that in some cases sampling points were located away from roads; the percentage of points near a street was 93, 95 and 78% in Cáceres, Don Benito and Olivenza, respectively.

The volume of traffic was determined and categorized visually (cars, heavy vehicles, and motorcycles) during sampling, and other relevant information (noise sources, meteorological conditions, street dimensions, road surface type, conservation of road surface, etc.) was also noted. At each measurement, L_{Aeq}, L_{AF1}, L_{AF10}, L_{AF50}, L_{AF90}, L_{AF99}, $L_{AF\max}$, and $L_{AF\min}$, in dBA, were recorded. Although some objections to the use of L_{Aeq} have been raised (Can *et al.*, 2008), for the present study only the results for this indicator will be analyzed due to its importance as a reference indicator of the assessment of noise and its effects on people in standards and legislation (ISO 1996-1, 2003; COM, 2002).

2.4. Statistical methods

The noise value assigned to each sampling point (G_{ij}) was the energy average of the different measurements carried out at that point (three or four measurements, as mentioned). Uncertainty of sampling point noise value was calculated according to the ISO 1996-2 (ISO 1996-2, 2007).

The noise value assigned to each square of the grid ($\widehat{S}$) was the arithmetic mean value of the four nodes of the square. The noise value assigned to each square is taken to be the expected value for every point located inside that square. Uncertainty of this value was calculated from uncertainty of sampling points, according to the GUM (ISO/ IEC Guide 98-3, 2008).

To study the predictive capacity of the grid method, all the grids larger than the 200 m reference grid included at least one measured 200 m sampling point inside each square. The actual sound level of these points, G_{ij}, was compared with the expected value, $\widehat{S}(G_{ij})$, of the corresponding square of the grid. The difference between the two will be termed the *prediction error*: $e_{I:hl} = G_{ij} - \widehat{S}(G_{ij})$.

Information about the tests used as part of the Analysis of Variance (ANOVA) can be found elsewhere (Sahai, Ageel, 2000).

3. Results and discussion

In this section, after a global description of all the measurements carried out, we shall first present the results of the study of the city of Cáceres (Subsecs. 3.2 to 3.5). The conclusions obtained for Cáceres will be compared with those obtained for the results of Don Benito and Olivenza (Subsec. 3.6).

3.1. Overall description of measurements

As shown in Tables 2 and 7, more than one thousand measurements were carried for this study (645, 344 and 144 in Cáceres, Don Benito and Olivenza, respectively). In Fig. 4, the bar charts of all these measurements are shown. As it can be seen the major percentage of measurements was in the 55–70 dBA interval.

As mentioned, in the major part of measurements traffic flow was present (93, 95 and 78% in Cáceres, Don Benito and Olivenza, respectively). The mean values of flow of light vehicles (with mass under 3.500 kg), heavy vehicles (trucks and buses) and motorcycles were 285, 16, and 12 vehicles per hour in the city of Cáceres, whilst in Don Benito they were 228, 10, and 7

Table 2. Overall study of the city of Cáceres for all the alternatives studied of the grid method. I: grid of 200 metres; II–III: 45°-rotated 200 metre grid (grid of 283 metres) (two alternatives); IV–VII: 400 metre grid (four alternatives); VIII–XVI: 600 metre grid (nine alternatives); XVII–XX: 800 metre grid (four alternatives). Symbols used: $\overline{x}$ – arithmetic mean value; σ_{n-1} – standard deviation; $\sigma_{\overline{x}}$ – typical error; $k = 1.96$.

	Alternative									
	I	II	III	IV	V	VI	VII	VIII	IX	X
Grid size (metres)	200	283	283	400	400	400	400	600	600	600
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of measurements (dBA)	61.3±0.5 (6.6)	61.7±0.8 (6.8)	61.1±0.7 (6.5)	60.6±1.0 (6.2)	61.1±1.1 (7.0)	61.4±1.1 (6.6)	62.5±1.0 (6.4)	62.8±1.3 (5.6)	60.7±2.0 (7.9)	59.8±1.7 (6.7)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of sampling points (dBA)	61.8±0.8 (6.1)	62.3±1.2 (6.2)	61.6±1.2 (6.1)	61.2±1.5 (5.7)	61.7±1.7 (6.3)	61.9±1.8 (6.2)	63.0±1.7 (6.0)	63.4±2.0 (5.0)	61.3±3.2 (7.3)	60.4±2.7 (6.3)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of grid squares	61.9±0.5 (3.5)	62.5±0.7 (3.1)	61.8±0.7 (3.2)	61.6±1.2 (3.4)	62.0±1.1 (3.4)	61.3±1.0 (2.8)	63.3±0.9 (2.3)	63.8±1.5 (2.5)	61.9±2.5 (4.1)	61.3±2.1 (3.4)
Sampling points over 55 dBA(%)	85.6	87.3	85.6	86.6	83.6	83.3	91.8	100	75.0	85.7
Sampling points over 65 dBA(%)	31.6	34.3	30.8	24.5	30.9	33.3	38.8	39.1	35.0	28.6
Squares over 55 dBA(%)	97.0	98.6	100	93.8	97.1	100	100	100	90	90
Squares over 65 dBA(%)	24.4	21.1	16.9	15.6	23.5	10.3	20.7	30.0	20.0	10.0
	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX
Grid size(metres)	600	600	600	600	600	600	800	800	800	800
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of measurements (dBA)	63.7±1.9 (7.0)	58.3±1.4 (5.4)	63.0±1.8 (6.6)	63.2±1.6 (6.3)	60.5±1.7 (6.5)	59.7±1.6 (6.1)	64.6±1.7 (5.3)	58.8±2.2 (6.3)	59.2±2.2 (6.4)	59.0±1.8 (5.7)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of sampling points (dBA)	64.3±3.1 (6.5)	58.5±2.4 (5.3)	63.5±2.9 (6.2)	63.6±2.7 (6.0)	60.9±2.7 (6.1)	60.1±2.6 (5.8)	64.9±2.7 (4.8)	59.8±3.7 (6.2)	59.7±3.6 (6.1)	59.7±2.7 (5.0)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of grid squares	64.2±1.7 (2.4)	58.8±1.8 (2.8)	62.8±1.6 (2.4)	64.0±1.0 (1.6)	61.3±1.4 (2.2)	59.8±1.5 (2.4)	64.4±1.1 (1.2)	60.4±3.1 (3.5)	60.4±1.9 (2.0)	61.3±2.0 (2.4)
Sampling points over 55 dBA (%)	94.1	72.2	94.4	89.5	84.2	73.7	91.7	72.7	81.8	84.6
Sampling points over 65 dBA (%)	52.9	11.1	27.8	42.1	26.3	21.1	50	27.3	27.3	15.4
Squares over 55 dBA (%)	100	100	100	100	100	100	100	100	100	100
Squares over 65 dBA (%)	37.5	0	11.1	30.0	10.0	0	20.0	0	0	0

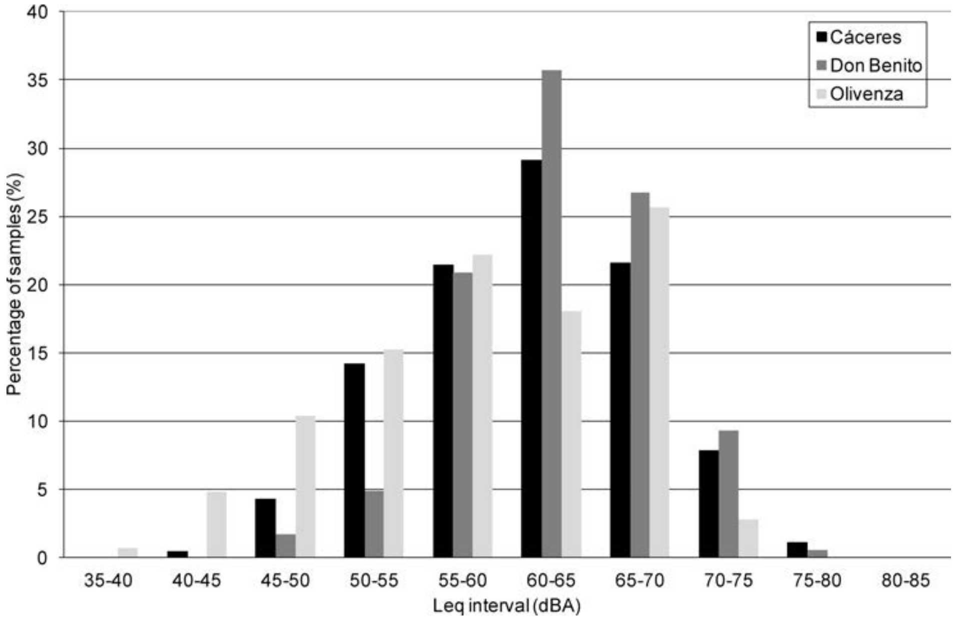

Fig. 4. Bar charts of the measurements carried out in the different studied cities.

vehicles per hour, respectively, and in Olivenza these values were 68, 5, and 4 vehicles per hour, respectively.

3.2. Overall noise assessment of the city

One of the aims of noise studies is to give an overall picture of a city's noise situation. This objective is sometimes extended to determining the number of inhabitants exposed to harmful noise levels. Thus in general, two different values are given: firstly an overall value for the noise in the city, and secondly the percentage of noise values that surpass a certain threshold value. For this study, the 55 dBA value given by the WHO (2000) for serious annoyance in daytime and the 65 dBA value suggested by the OECD as the daytime exposure limit (OECD, 1986) were used as reference values.

Table 2 presents the average values obtained for each grid studied. These values are the means of the measurements carried out, the means of the sampling point values, and the means of the grid square values (the numbers of measurements, sampling points, and grid squares of each case were given in Table 1). The table also gives the percentage of values of the sampling points or of the squares that surpass the aforementioned two reference values.

As a control of the data corresponding to each grid, the values of each set of sampling points $[G_{ij}]$ were analyzed by the Shapiro-Wilk test, resulting in only the data of one of the 800 metre grids showing a significantly non-normal distribution. The ANOVA test found no significant differences within any of the groups of grids (there being four groups established: the 283 metre grid groups – with two configurations; the 400 metre grid group – with four configurations; and the 600 and 800 metre grid groups – with 9 and 4 configurations, respectively).

We shall take as reference the value for the 200 metre grid (column 1 of Tables 1 and 2) to discuss the mean values obtained for the other grids applied to the city map. One observes in the Table 2 that, for the two alternatives of the 283 metre grid size which have fewer than half the points of the reference (200 m) grid, the mean values calculated for the city differed from the reference by less than 0.6 dBA. For the four possible alternatives of the 400 metre grid the mean values differed from the reference by less than 1.2 dBA. And for the different alternatives of the 600 and 800 metre grids (nine and four, respectively) the mean values differed from the reference in the range −3.0 dBA to +2.4 dBA and −3.3 dBA to +2.5 dBA, respectively. This observed behaviour is not far from that expected statistically when a reduced sample of data of a studied population is taken by randomly selecting points. Thus, as mentioned above, the ANOVA found no significant differences within the noise values of the sampling points of each group of grids (for instance, among the nine alternatives of the 600 metre grid). Also, considering the mean value and the 95% confidence intervals (Fig. 5), one observes that almost all the results overlap.

Considering the typical error of the mean values (also shown in Table 2), as it can be seen and as it could be expected, these values increase when increasing the size of the grid for the three values [those obtained from the measurements, points and grids squares]. Thus, considering, as example, uncertainty associated to the city's overall mean values obtained from the sampling points values, the mean values of the calculated uncertainties are close to 1 dBA for the 200 and 283 me-

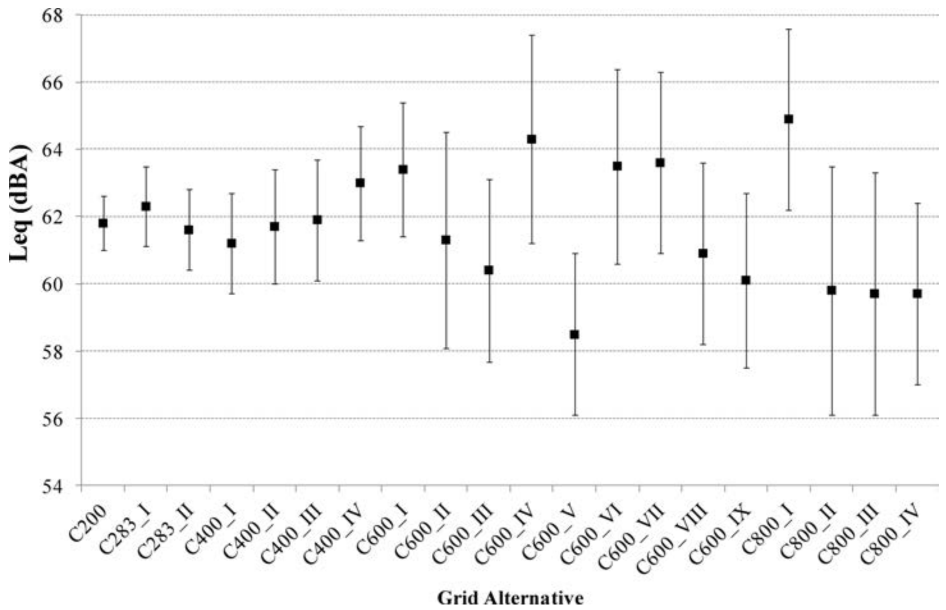

Fig. 5. Average value and 95% confidence intervals obtained for the different grid sizes.

tre grid sizes, increasing to values between 2 dBA and 3.5 dBA for the 600 and 800 metre grid sizes, respectively.

Therefore, results from mean values and typical errors are both indicating that the increase in the size of the grid produces an increase in the uncertainty of the city mean values. Grid size values higher than 400 m involves uncertainties of the calculated mean values greater than 2 dB.

With respect to the standard deviations associated with the calculated mean values (Table 2) which provides us information about the dispersion of the data we can see that they remained practically constant for all the grid sizes in all the three types of mean values (from measurements, points or grid squares) even though the numbers of values used in the calculation are very different. This behaviour is indicative of no great change in the variability of the noise data with the variation of the number of measurements points Comparing the values associated with the means of the measurements and the means of the noise values of the points, the standard deviations are quite similar in all the alternatives studied. This would be the case if the three measurements of each sampling point were similar, and is thus coherent with an adequate characterization of the noise at the point in the period of the day studied with the temporal sampling strategy used. Finally, the standard deviation of the mean of the squares is clearly lower than the standard deviation of the mean of the noise values of the points. This behaviour is indicative of a clear difference between the four values of the grid squares with, when the value of each square is obtained from the average values of its four points, the variability being reduced as the higher and lower noise values compensate each other. This reduction of the variability in sound levels will be confirmed below.

Table 2 also lists the percentages of sampling points whose noise values surpassed some reference threshold. As one observes, as the grid size was increased, the changes in the percentage of sampling points surpassing these two thresholds relative to the 200 metre grid reference percentages were slight for the 283 metre grid (in absolute terms, from +0.0 to +1.7% and from −0.8 to +2.7% for 55 dBA and 65 dBA levels, respectively), appreciable for the 400 metre grid (in absolute terms, from −2.3 to +6.2% and from −7.1 to +7.2% for the 55 dBA and 65 dBA levels, respectively), and marked for the 600 and 800 metre grids (in absolute terms for the 600 metre grid, from −13.4 to +14.4% and from −20.5 to +21.3% for the 55 dBA and 65 dBA levels, respectively). These results indicate a loss of sensibility for noise impact or noise exposure assessment when increasing the size of the grid.

Finally, the behaviour for the percentages of squares whose noise values surpass these threshold levels (Table 2) is clearly different from that of the sampling point values. One observes from the table that with increasing grid size, there was generally an increase in the percentage of squares with values over 55 dBA, but a decrease in the percentage of squares with values over 65 dBA. This is again indicative of a reduction in the variability of the values when averaging them over the corners of each square, as was described above.

A partial conclusion that may be drawn from the results discussed in this subsection is that, bearing in mind the uncertainty due to the number of measurements, the study of noise by the grid method can provide good data with which to evaluate a town's average noise level with a relatively small number of measurements. Nevertheless, to obtain the percentage of values that surpass a certain threshold, the major differences observed for grids equal or coarser than 400 metres seem to indicate that such large sizes can lead to important mistakes in the estimates. Even for for the 283 metre grid, comparing to the 200 metre grid, we found a variation in the percentage of squares with values over 65 dBA, from 24.4% to 16.9% (reduction of 30%).

3.3. Assignation of a noise value to a region of the city

One of the major aims of the noise assessment is to determine which part of the population is affected by noise. In the grid method, one way of doing this is to assign to the area inside each grid polygon a noise value calculated from the values at its corners.

Differences between the grid sizes and alternatives were analyzed in two ways. In one approach, we focused on the percentages of squares whose noise values surpassed the two threshold levels (55 and 65 dBA). As was noted above, an increase in the grid size led qualitatively to the disappearance of the quieter and noisier regions of the city. This implies that these regions will be overestimated and underestimated, respectively, i.e., that the estimation of the noise levels supported by the affected population will be erroneous. In the other approach, we analyzed the possible change in the value of a particular region of the map (the areas of the 200 metre grid were taken as reference). This analysis was carried out only for the four alternatives of the grid with a size of 400 metres which, according to the previous subsection, would seem to give results comparable to those of the reference values of the 200 metre grid. Table 3 presents the results for the variations in the values assigned to these areas (initial squares of the 200 metre grid). One observes that more than 10% of the initial squares presented variations greater than 5 dBA, and more than 30% presented variations greater than 3 dBA in the value assigned to the interior of the square. Table 4 presents

Table 3. Variation in the noise value of a square of the 200 metre grid size when this region is included in a square of the 400 metre grid size. I: 400 metre grid (alternative I); II: 400 metre grid (alternative II); III: 400 metre grid (alternative III); IV: 400 metre grid (alternative IV). Initial squares in the 200 metre grid size: 168.

	I	II	III	IV
Initial squares (200 m) that are inside the new grid (400 m)	128	136	116	116
Variations greater than 3 dBA	46	58	53	37
Variations greater than 3 dBA (%)	35.9	42.6	45.7	31.9
Variations greater than 5 dBA	17	26	17	16
Variations greater than 5 dBA (%)	13.3	19.1	14.7	13.8

Table 4. Variation with respect to the reference levels (55 and 65 dBA) of the noise value of a square of the 200 metre grid size when this region is included in a square of the 400 metre grid size. I: 400 metre grid (alternative I); II: 400 metre grid (alternative II); III: 400 metre grid (alternative III); IV: 400 metre grid (alternative IV). Initial squares in the 200 metre grid size: 168.

		I	II	III	IV
Values initially over 65 dBA	The value is still over 65 dBA	8	20	4	12
	The value is under 65 dBA	22	17	28	16
	No data	11	4	9	13
Values initially under 65 dBA	Change to a value over 65 dBA	9	12	8	12
	Still under 65 dBA	88	88	77	77
	No data	30	27	42	38
Values initially over 55 dBA	It was also over 65 and now is over 55 dBA	30	37	32	85
	It was under 65 and now is over 55 dBA	89	95	83	28
	It was also over 65 and now is under 55 dBA	0	0	0	0
	It was under 65 and now is under 55 dBA	3	4	1	1
	No data	41	27	47	49
Values initially under 55 dBA	Change to a value over 55 dBA	0	0	1	3
	Still under 55 dBA	5	1	0	0
	No data	0	4	4	2

the results for the selected regions (initial squares of the 200 metre grid) compared to the two threshold levels (55 and 65 dBA). One observes that between 16 and 28 of the 41 squares with an initial value (in the 200 metre grid) over 65 dBA were evaluated at levels below that threshold in the 400 metre grid. Also, of the 127 squares initially under 65 dBA, between 8 and 12 surpassed this reference level in the 400 metre grid. The difference between these two sets of values (the number of squares that changed in surpassing or not the threshold value) is congruent with the aforementioned reduction in variability in calculating the values inside the squares. For the 55 dBA threshold, very few squares were initially below this value, and the conclusions than can be drawn are therefore less clear. Nevertheless, one does observe again the reduction in variability of the sound values.

One can conclude from this section that increasing the size of the grid reduces the noisier zones of the city, and thus underestimates the noise to which that part of the population is subjected. For the quieter zones, the effect is the contrary. The reduction of these zones by increasing the grid size leads to an overestimate of the noise to which this portion of the population is subjected.

As a partial conclusion of the results discussed in this subsection, the 400 metre grid size seems to give values of the noise exposure that are quite different from those obtained with the 200 metre grid size.

3.4. The necessity for new measurements according to ISO 1996-2

According to ISO 1996-2: 1987 (ISO 1996-2, 1987), if the difference between two adjacent nodes is greater than 5 dBA, an additional sampling point in the middle of these two points should be measured. This recommendation is also part of ISO 1996-2: 2007 (ISO 1996-2, 2007).

This recommendation was not taken into account in the study of the 200 metre grid, since this was taken to be the reference size. The increase in the number of sampling points according to the ISO recommendation was calculated for all grid sizes (Table 1). One observes that for all the sizes and alternatives analyzed, more than 50% of new points are necessary (indeed, this increase is generally greater than 75% of the initial points of a given alternative).

In some of the sizes analyzed, such as the case of the 400 metre grid, there is a measured value in the middle of each side of the square, and thus it was possible to analyze the ISO 1996-2 recommendations. To this end, all four alternatives of the 400 m grid were studied (the results are presented in Table 5).

Table 5. Analysis of the ISO 1996-2 recommendation on the necessity for new measurements in the middle of the sides of the squares. I: 400 metre grid (alternative I); II: 400 metre grid (alternative II); III: 400 metre grid (alternative III); IV: 400 metre grid (alternative IV).

	I	II	III	IV
Segments with difference greater than 5 dBA	**42**	**53**	**46**	**49**
Intermediate point has difference with both ends less than 5 dBA	6	5	1	4
Intermediate point has difference greater than 5 dBA with one of the ends	30	35	31	34
Intermediate point has difference greater than 5 dBA with both ends	6	13	14	11
Segments with difference less than 5 dBA	**40**	**35**	**29**	**27**
Intermediate point has difference with both ends less than 5 dBA	18	17	18	15
Intermediate point has difference greater than 5 dBA with one of the ends	7	5	1	6
Intermediate point has difference greater than 5 dBA with both ends	15	13	10	6

Considering first those adjacent points which differ by more than 5 dBA, one observes in the table that only for a very small percentage of these intermediate points (between 2% and 14%) did the noise value differ by less than 5 dBA relative to the two adjacent points. For the rest of the intermediate points recommended by ISO 1996-2, the value differed by more than 5 dBA relative to one (or even to both) of the adjacent points, and thus one (or two) additional intermediate point(s) would have to be measured according to the ISO standard. Indeed, after measuring the first set of new points indicated by the ISO 1996-2 recommendation (42, 53, 46, and 49 for the four different alternatives of the 400 metre grid), an even greater number of new points would have to be measured in a second step according to that same recommendation (42, 61, 59, and 56, respectively, in all cases more than 100% of new points).

In considering the segments whose end points had noise values which did not differ by more than 5 dBA, and hence according to the ISO 1996-2 recommendation did not require intermediate points to be measured, one finds that in approximately 50% of the cases the intermediate point had a noise value that now differed by more than 5 dBA from either one or both of the end points.

These results seem to suggest that the need for measurements at intermediate points recommended by ISO 1996-2 implies a continuous process of measuring at new points in a process that would probably finish when the distance between points was so small that the entirety of a street segment had been measured.

Furthermore, the present results showed that, even in the 50% of the intermediate points where the ISO 1996-2 standard did not recommend new measurements from probably assuming that there would be an almost constant value in the noise field, the results showed that this assumption is a mistake.

3.5. Predictive capacity of the grid method

To study the predictive capacity of the method, the difference was calculated between the values measured for the points inside the squares (G_{ij}) (as noted above, in all the grid sizes greater than 200 m there was at least one measured point inside the square) and the predicted values, i.e., the noise values assigned to the area inside the grid squares calculated by averaging their corners – $\widehat{S}$. This value was termed the prediction error $e_{I:hl}$, as explained above. The new points considered for the calculation of the prediction errors were not used for the grid calculations. They were always located inside the squares, with points in the sides of the square never being considered.

Table 6 lists the statistics associated with these prediction errors. From this table, one can draw the following conclusions.

Firstly, the median values of the prediction errors $e_{I:hl}$ for the 283-metre grid size were below 1 dBA, indicating that these prediction errors were distributed around the value zero, which is statistically coherent. For greater grid sizes, there were some median values that were greater than 2 dBA, indicating a certain bias in the results. Obviously, such a bias is undesirable, and these greater grid sizes would not be good options for the characterization of the noise of this city.

Table 6. Overall values of the prediction error $[e_{I:hl}]$. II–III: 45°-rotated 200 metre grid (grid of 283 metres) (two alternatives); IV–VII: 400 metre grid (four alternatives); VIII–XVI: 600 metre grid (nine alternatives); XVII–XX: 800 metre grid (four alternatives).

	Alternative																			
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX
Grid size (meters)	200	283	283	400	400	400	400	600	600	600	600	600	600	600	600	600	800	800	800	800
Mean value of the prediction errors (dBA)		−0.9	0.6	−0.6	1.4	1.3	−2.2	−2.3	0.7	0.3	−2.4	4.0	0.9	−2.0	0.9	1.9	−1.8	1.5	2.4	2.2
Median value of the prediction errors (dBA)		−0.8	0.6	0.2	0.2	1.0	−2.2	−1.6	0.9	0.6	−0.1	4.6	1.3	−1.6	0.9	2.7	−2.0	0.9	3.1	1.7
Mean value of the absolute values of prediction errors (dBA)		4.3	4.4	5.2	5.4	5.4	4.5	5.7	5.2	5.0	5.7	6.5	4.9	4.5	4.6	5.2	5.5	5.2	5.0	5.3
Number of points		71	71	32	34	29	29	40	40	40	32	36	36	40	40	40	45	45	36	54
Sum of the uncertainties ($k = 1$) < prediction error (% of points)		57.7	52.1	71.9	55.9	37.9	48.3	67.5	65.0	52.5	50.0	77.8	58.3	52.5	50.0	57.5	60.0	57.8	63.9	53.7
Sum of the uncertainties ($k = 1.96$) < prediction error (% of points)		19.7	19.7	31.3	29.4	24.1	17.2	35.0	30.0	25.0	34.4	55.6	30.6	30.0	22.5	35.0	40.0	28.9	27.8	37.0

Secondly, the means of the absolute values of the prediction errors indicated a major deviation of the new data from the predictions of the grid method. For all the alternatives studied, this mean value was greater than 4 dBA, indicating that the grid method may be unsuitable for noise evaluation in locations other than the sampling points.

Thirdly, considering the uncertainties associated both to the sampling point and to the square of the grid, in a high percentage of the sampling points (usually over 50%), the value of the prediction error was higher than the sum of these two uncertainties for a coverage factor of 1. These percentages were also important for a coverage factor of 1.96 (near 20% or higher) As it can be seen in the city of Cáceres this value increases when increasing the grid size, which corroborates the fact that an increase in the size of the grid size implies a loss in the accuracy and the predictive capacity of the method

Finally, in a previous work (Barrigón *et al.*, 2011) the prediction errors of the grid method were compared with those of an alternative method (the categorization method). The results showed that the prediction errors associated with the grid method were greater than those of the categorization method (Barrigón *et al.*, 2011).

3.6. Application of the same method to the smaller towns of Don Benito and Olivenza

As mentioned in the Introduction, in order to enrich the study and to corroborate the above partial conclusions, the same methodological approach was applied to the towns of Don Benito and Olivenza. As these towns are smaller than Cáceres, only 200 to 400 metre grid sizes were considered. Table 7 provides information about the number of measurement points and the number of grid squares of each alternative

Table 7. Grid size, measurement points, number of measurements, grid squares, new necessary points according to ISO 1996-2 recommendations, and percentage represented by these new necessary points with respect to the measurement points employed for the different alternatives of each grid method analyzed in the towns of Don Benito and Olivenza. I: grid of 200 metres; II–III: 45°-rotated 200 metre grid (grid of 283 metres) (two alternatives); IV–VII: 400 metre grid (four alternatives).

	Don Benito							Olivenza						
	Alternative							Alternative						
	I	II	III	IV	V	VI	VII	I	II	III	IV	V	VI	VII
Grid size (metres)	200	283	283	400	400	400	400	200	283	283	400	400	400	400
Measurement points	86	43	41	21	21	20	21	48	23	19	12	11	10	10
Measurements	344	172	164	84	84	80	84	144	69	57	36	33	30	30
Grid squares	65	28	27	12	12	11	12	32	14	10	5	5	4	4
Minimum additional new necessary points	68	36	36	15	14	17	18	51	22	19	12	11	9	8
Minimum additional new necessary points (%)	79	84	88	71	67	85	86	106	96	100	100	100	90	80

Table 8. Overall study of the towns of Don Benito and Olivenza for all the alternatives studied of the grid method. I: grid of 200 metres; II–III: 45°-rotated 200 metre grid (grid of 283 metres); IV–VII: 400 metre grid. Symbols used: $\overline{x}$ – arithmetic mean value; σ_{n-1} – standard deviation; $\sigma_{\overline{x}}$ – typical error; $k = 1.96$.

	Don Benito							Olivenza						
	Alternative							Alternative						
	I	II	III	IV	V	VI	VII	I	II	III	IV	V	VI	VII
Grid size (metres)	200	283	283	400	400	400	400	200	283	283	400	400	400	400
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of measurements (dBA)	63.1±0.6 (5.5)	63.8±0.8 (5.5)	62.2±0.8 (5.5)	64.3±1.2 (5.8)	61.9±1.2 (5.4)°	62.8±1.2 (5.4)	63.2±1.1 (5.3)	58.9±1.3 (7.9)	58.7±1.9 (8.2)	59.1±1.9 (7.4)	56.1±2.5 (7.5)	58.6±2.8 (8.2)	57.3±3.1 (8.7)	62.5±2.2 (6.1)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of sampling points (dBA)	64.0±1.0 (4.9)	64.9±1.5 (4.9)	62.9±1.5 (4.9)	65.3±2.2 (5.1)	62.6±2.2 (5.1)	63.6±2.0 (4.5)	64.4±2.1 (4.9)	59.8±2.0 (7.2)	59.6±3.1 (7.6)	59.7±3.2 (7.0)	57.1±4.1 (7.2)	59.9±4.3 (7.3)	58.1±5.4 (8.4)	63.0±3.4 (5.6)
$\overline{x} \pm k \cdot \sigma_{\overline{x}}(\sigma_{n-1})$ of grid squares	64.0±0.6 (2.4)	65.1±0.8 (2.2)	62.9±0.7 (1.9)	65.8±1.2 (2.1)	63.3±1.3 (2.4)	63.8±0.9 (1.5)	64.2±0.9 (1.6)	60.4±1.1 (3.0)	60.1±1.8 (3.4)	60.2±1.1 (1.7)	57.1±2.0 (2.3)	59.5±2.4 (2.7)	59.0±3.3 (3.3)	62.8±1.6 (1.7)
Sampling points over 55 dBA (%)	95.4	95.4	95.1	95.2	95.2	95.0	95.2	75.0	73.9	73.7	58.3	63.6	70.0	90.0
Sampling points over 65 dBA (%)	47.7	53.5	41.5	61.9	33.3	50.0	42.9	29.2	34.8	21.1	8.3	36.4	30.0	40.0
Squares over 55 dBA (%)	100	100	100	100	100	100	100	93.8	92.9	100	100	100	100	100
Squares over 65 dBA (%)	32.3	39.3	11.1	66.7	16.7	9.1	33.3	6.3	7.1	0	0	0	0	25.0

analyzed. One observes that there were clearly fewer measurement points and grid squares than were used for the study in the city of Cáceres.

Table 8 presents the same information of the overall noise assessment of these two towns as did Table 2 for the city of Cáceres. One observes that the mean values obtained, their typical errors and the standard deviations show a similar behaviour to those described for the city of Cáceres. The behaviour of the percentage of measurements that surpass the studied thresholds (55 and 65 dBA) is also similar, although in this case the percentage differences relative to the reference value (200 metre grid) for the 283 metre grid are greater (in absolute terms) for the sampling points over 65 dBA (with differences of around 6% in both Don Benito and Olivenza). For the 400 metre grids, that in the study of Cáceres seems to be an appropriate size, but in Don Benito, except for the 55dBA reference level, there were large differences (for example, the percentage of points over 65 dBA in two of the 400 metre grid studies differed by more than 13% from the reference value), and in Olivenza the difference reached more than 20% in one of the cases.

With respect to the assignation of a noise value to a region of the town, for Don Benito between 2.1% and 6.3% of the initial squares presented variations greater than 5 dBA, while between 20.5% and 37.5% of the initial squares presented variations greater than 3 dBA. For Olivenza these ranges were 0–30% and 25–80%, for variations greater than 5 dBA and 3dBA, respectively. These results are slightly lower for variations over 5 dBA but similar for variations over 3 dBA to those obtained in the city of Cáceres. Considering the grid squares that initially presented a value over 65 dBA in the town of Don Benito (21), between 2 and 12 of them were evaluated at levels below that threshold in the 400 metre grid. Of the 44 squares initially under 65 dBA in that town, between 5 and 20 surpassed this threshold in the 400 metre grid. For the rest of the variations in Don Benito and for all of them in Olivenza, the data were insufficient to allow conclusions to be drawn, but the two cases described for Don Benito are congruent with the results for Cáceres, and similar partial conclusions can be drawn.

With respect to the necessity for new measurements according to ISO 1996-2, the numbers of new points needed (listed in Table 7) are similar in percentage terms, and even higher in Olivenza, than for the city of Cáceres. Considering for the 400 metre grids the intermediate point of each segment (Table 9), one observes that, as also in the results for the city of Cáceres, only in a small proportion of cases (between 0% and 24%) does the intermediate point between two vertices which differ by more than 5 dBA present a noise value which differs by less than 5 dBA from either of the two adjacent points. Again, approximately 50% of the intermediate points between two vertices which differ

Table 9. Analysis of the ISO 1996-2 recommendation on the necessity for new measurements in the middle of the sides of the squares in the towns of Don Benito and Olivenza. I: 400 metre grid (alternative I); II: 400 metre grid (alternative II); III: 400 metre grid (alternative III); IV: 400 metre grid (alternative IV).

	Don Benito				Olivenza			
	I	II	III	IV	I	II	III	IV
Segments with difference greater than 5 dBA	**15**	**14**	**17**	**18**	**12**	**11**	**8**	**8**
Intermediate point has difference with both ends less than 5 dBA	3	2	4	3	0	0	0	0
Intermediate point has difference greater than 5 dBA with one of the ends	11	9	10	11	7	3	6	4
Intermediate point has difference greater than 5 dBA with both ends	1	3	3	4	5	8	2	4
Segments with difference less than 5 dBA	**17**	**18**	**13**	**14**	**4**	**4**	**5**	**5**
Intermediate point has difference with both ends less than 5 dBA	9	6	6	6	2	1	2	2
Intermediate point has difference greater than 5 dBA with one of the ends	5	8	4	6	1	1	0	3
Intermediate point has difference greater than 5 dBA with both ends	3	4	3	2	1	2	3	0

Table 10. Overall values of the prediction error [$e_{I:hl}$] for the towns of Don Benito and Olivenza. II–III: 45°-rotated 200 metre grid (grid of 283 metres) (two alternatives); IV–VII: 400 metre grid (four alternatives).

	Don Benito							Olivenza						
	Alternative							Alternative						
	I	II	III	IV	V	VI	VII	I	II	III	IV	V	VI	VII
Grid size (meters)	200	283	283	400	400	400	400	200	283	283	400	400	400	400
Mean value of the prediction errors (dBA)		−2.5	2.6	−1.9	−0.8	−1.3	2.0		0.3	2.5	8.7	1.6	4.2	−3.5
Median value of the prediction errors (dBA)		−2.7	2.3	−2.5	−0.8	−0.7	2.2		0.3	0.5	5.1	1.8	5.4	−3.3
Mean value of the absolute values of prediction errors (dBA)		3.8	4.3	4.3	4.6	3.7	3.7		6.4	5.2	8.7	4.8	7.5	4.1
Number of points		28	27	12	12	11	12		14	10	5	5	4	4
Sum of the uncertainties ($k = 1$) < prediction error (% of points)		28.6	33.3	33.3	41.7	45.5	33.3		50.0	40.0	80.0	20.0	75.0	50.0
Sum of the uncertainties ($k = 1.96$) < prediction error (% of points)		14.3	14.8	8.3	16.7	9.1	0.0		35.7	30.0	40.0	20.0	25.0	0.0

by less than 5dBA present a noise value which differs by more than 5 dBA from at least one of the adjacent points.

Finally, Table 10 presents the results respecting the predictive capacity of the method for the towns of Don Benito and Olivenza. The results for Olivenza are similar to those for Cáceres: while the 283 metre grids have low median values of the prediction errors, the 400 metre grids have median values which are clearly greater, indicative of a certain bias in the results. For Don Benito, the medians of the prediction errors are similar for the 283 metre and the 400 metre grids, and indicative of bias in all the cases. The means of the absolute values of the prediction errors are similar to those obtained in Cáceres, again indicating the risk of using the grid method to estimate noise levels in locations other than at the points actually sampled.

Finally, considering the uncertainties associated both to the sampling point and to the square of the grid, the value of the prediction error was higher than the sum of these two uncertainties for a coverage factor of 1 in a high percentage of the sampling points, mainly in Olivenza. In these two cities it is not clear the increase of this value when increasing the grid size, which was observed in Cáceres.

4. Conclusions

Some conclusions have already been outlined above. They can be summarized as follows:

The grid method can be considered as a very efficient and inexpensive form of making an overall assessment of the noise in a town. The influence of the size of the grid did not seem to be relevant apart from the widening of the confidence interval with increasing grid size. Thus, grid size coarser than 400 metres leads to uncertainties of the calculated mean values greater than 2 dB.

For the assessment of how the population may be subject to noise levels, however, the method seems to be very sensitive to the size of the grid. Thus, increasing the size of the grid caused an underestimate of this incidence in the noisier parts of the city, and an overestimate in the quieter parts. Based on the present results, grid sizes coarser than 283 metres seem to be inadvisable.

The predictive capacity of the grid method seems to be very limited in light of the present results. Thus, taking as reference the 200 metre grid, the use of a 400 metre grid would imply major variations in the values assigned to the points inside the grids. Also, for the points in the centre of the 283 metre grid, the mean value of the absolute values of the prediction error was greater than 3.5 dBA.

The prediction errors associated with the method can be considered as being large, and they increased with increasing size of the grid.

Finally, the measurement of new points following the ISO 1996-2 recommendation would seem to imply an almost continuous need to measure new points at an ever finer scale since the noise values of the intermediate points implied the need to measure a further set of new intermediate points. Furthermore, the mere non-existence of 5 dBA of difference between two adjacent points did not imply that the intermediate point would also lie within this range.

Future researches on the grid method considering, for example, the reduction the size of the grid, comparing results of grids with the same spacing but different orientations or measuring intermediate points. could be interesting for going into depth in the analysis of this sampling (mapping) procedure.

Acknowledgments

This work was partially supported by the *Ministerio de Educación y Ciencia* Project No. TRA2006-03115) and the *Consejería de Infraestructuras y Desarrollo Tecnológico* of the *Junta de Extremadura* [Projects No. PRI06A271 PD10166 and GR10175] and the European Regional Development Fund (ERDF).

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