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Comparative analysis of methods to evaluate noise exposure and annoyance of people

Gaetano Licitra (1, 2), Elena Ascari (2) and Giovanni Brambilla (2)

(1) ARPAT (Tuscany Environmental Protection Agency), Florence, Italy
(2) CNR - IDASC (National Research Council – Institute of Acoustic and Sensors "O.M. Corbino"), Rome, Italy

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ABSTRACT

The availability of strategic noise mapping at European scale should allow comparing people exposure in each country but, unfortunately, different methods have been used so far. This paper focuses on sources of uncertainty in people exposure estimate depending on the method used to calculate noise levels at receivers and to assign levels to the buildings as well as population to each building. Results show that inaccurate estimate can lead to inappropriate allocation of economical resources within the action plans and can also affect results of epidemiological studies. Thus, the choice of the method should consider the aim of the study before assigning noise levels. Considering only the maximum noise level at the building façade is not suitable for epidemiological studies and definition of priorities of noise mitigation in action plans, as well as determination of noise scoring based upon highly annoyed dose-response curves.

INTRODUCTION

The aim of this study is to analyze the procedures for calculation of people exposure to noise in urban areas required by the European Environmental Noise Directive 2002/49/EC (END, [1]). In particular, sources of uncertainty in exposure assessment have been evaluated together with corresponding changes in annoyance estimate. The study was carried out referring to the case study of Pisa Municipality, where noise maps are available for every noise sources to be mapped (road, rail, airport and industries) [2]. To introduce the case study and highlight the main issues, simplified scenarios have also been considered.

The assessment of population exposure is strongly influenced by noise map calculation method. In fact, in addition to different standard models and their software implementation, there are also other variables that vary from State to State, like agglomeration definition, meteorological and demographic data availability etc. Some of these facets are considered in the Good Practice Guide GPG [3]: for instance different methods of inhabitant assignment to dwellings and buildings have been proposed. However, each Member State can have it is own procedure taking into account data availability (in Italy such assignment was examined in [4]).

This paper deals with determination of differences in the exposure arising from the façade noise level calculation and the assignment of population exposed to this level. Methods may lead to considerably different results, so it is interesting to evaluate which one is more representative of the real distribution of the exposure and, correspondingly, of annoyance that could be different from the one estimated by the strategic noise maps.

STATE OF ART AND SUPPORTING IDEAS

Data reported to the European Commission by Member States are very different from each other. Although the Directive 2002/49/EC has established the methodology to assign population to noise levels, it allows to apply national methods. The Directive requires that the maximum façade noise level is assigned to all the inhabitants in the building (hereafter called END distribution method). Other methods are currently used by Member States such as the German national method VBEB [5]. This method distributes equally the population among the receiver points located around the building and determines an exposure proportional to noise levels along all building's façades.

The END and national methods are implemented in almost all noise prediction softwares, so a comparison among these methods was thought to be interesting, as well as analysing how much the results are different from procedure to procedure.

Arana has already shown possible differences between END and VBEB methods [6]. He underlined the overestimation of END method and suggested a simplified method (*nearest point approximation method*, henceforth NEAR) to obtain results like those provided by VBEB. He compared these three methods for a small district of Pamplona (105 buildings in an area of 149600 m^2). For this scenario, he showed that NEAR and VBEB results are very similar but time spent to apply the former is shorter (1/9 points have to be calculated).

In this paper, a similar comparison is described for the Municipality of Pisa (40.000 buildings in an area of 185 km^2) where different distributions and calculation methods have been applied. The objective was to test the similarity found in

[6] and to extend the comparison to other methodologies and evaluate their suitability for epidemiological studies. In fact, many epidemiological studies report weak correlation between noise on the most exposed façade and annoyance: they underline the importance of the whole building exposure with particular attention to bedroom exposure.

EXPOSURE ASSIGNMENT METHODS: THE CASE STUDY OF PISA'S STRATEGIC NOISE MAP

Pisa was the first city in Tuscany to carry out strategic noise maps according to the Directive 2002/49/EC. Thus, overall exposure and acoustic maps for road, rail, aircraft and main industrial activities are available over the entire municipal territory.

Together with noise calculation (using a 5 m squared grid), a preliminary analysis of the population exposure was performed too. The END and VBEB methods have been applied to each building according to the automatic procedure implemented in the IMMI software that interpolates the noise levels calculated over the grid. The distribution of the population exposure obtained by VBEB resulted shifted on the left (maximum value about 3 dB smaller than the END one) and wider than the one by END as shown in Figure 1.

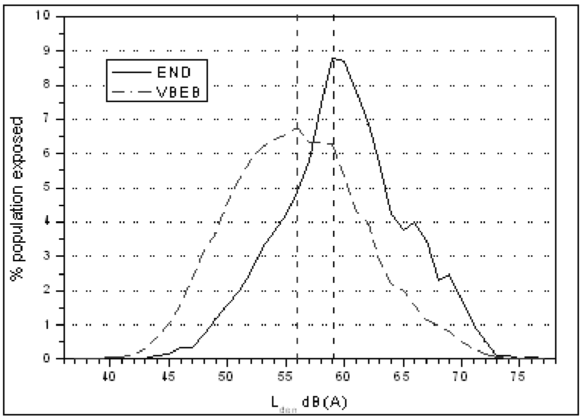

Figure 1. Comparison between END and VBEB method

Both distributions show a normal shape, as expected for high numbers. However, the fitting analysis pointed out that the Gaussian model fits very well the VBEB but not the END. Other theoretical models were tested but none seemed to match data better than the Gaussian one.

The Kolmogorov-Smirnov test for two samples was performed to verify if distributions belonged to the same statistical population. The test, based on expected maximum differences between distributions, confirmed their difference (D-statistic value 0.035 > 0.006 at 95% confidence level).

Considering the above results and the procedures available in the literature for assessing noise exposure of the population, it was considered interesting to analyse how much the observed differences depend on quantization of noise level distribution (a single level for all the inhabitants in the building) and how much on taking the maximum noise level. To perform this comparison, the following procedures have been considered:

1. All the inhabitants in the building assigned to the maximum noise level of receivers (END, according to the Directive 2002/49/EC [1]);
2. Inhabitants distributed over all the façade receivers (VBEB, according to the German regulation [5]);
3. Inhabitants distributed over the most exposed receivers (EXP, according to [7]);
4. Inhabitants assigned to the noise level averaged on the receivers (AVE);
5. Inhabitants assigned to the minimum noise level at receivers (MIN);
6. Inhabitants assigned to the closer grid point (NEAR, according to [6]).

All the listed methods, except NEAR, have been applied considering a receiver ring rounding each building at 4 m above ground and 2 m far away from the façade. All rings have been calculated interpolating the grid with an automatic spacing of receivers according to the VBEB standard method (see Figure 2).

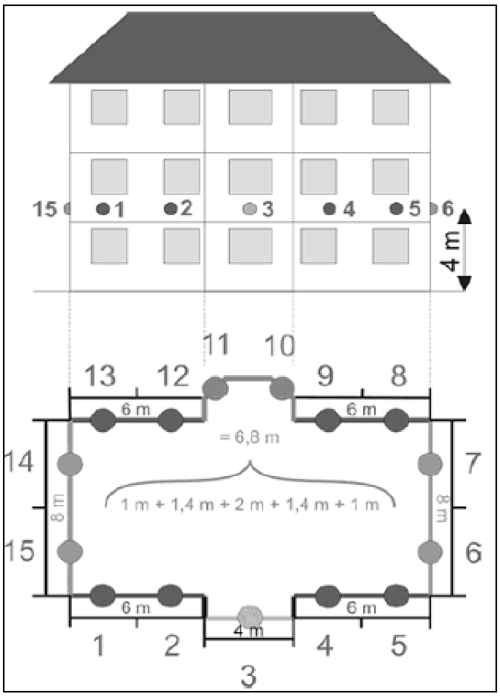

Figure 2. Standard VBEB receivers spacing [5]

Depending on the number of receivers over the ring, the software assigns a fraction of inhabitants to each point as the ratio between total inhabitants in the building and the number of receiver points; then the VBEB distribution is performed rounding noise levels to the nearest dB and summarizing inhabitant percentages by levels.

The EXP distribution is a cautious version of VBEB, as it distributes the inhabitants only over receivers exposed to noise levels exceeding the average level. This method distributes inhabitants according to the noise levels, so potentially in a different way depending on the time period.

The NEAR method is the only one processed without noise level software, as by GIS techniques the level of the closer external grid point is assigned to all the inhabitants in the building.

To clarify the above listed 6 procedures, an example of a building with 12 inhabitants and 14 receiver points is shown in Figure 3. The calculation points for each method are in black circle(s) and the line represents the road emitting the noise due to vehicle pass-by.

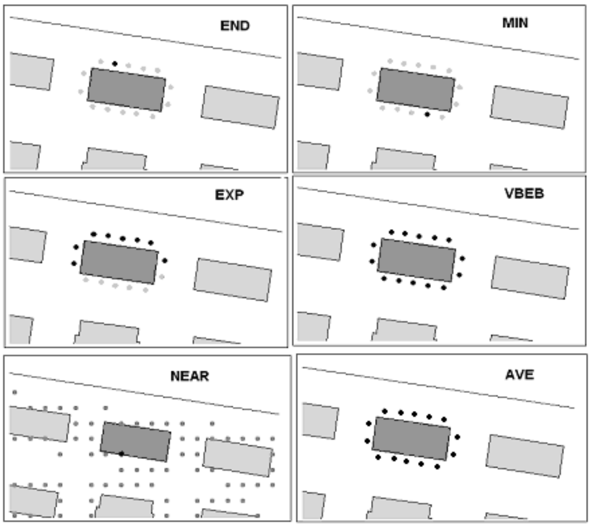

Figure 3. Calculation points for each method - example

Table 1 summarizes the results obtained by the methods producing a single value for the entire building.

Table 1. Results of single value distributions - example

Distribution	END	AVE	MIN	NEAR
L_{DEN}	70	64	53	66

Regarding methods providing more than a value, it has to be pointed out that a different quota of inhabitants is assigned to each receiver point by VBEB and EXP (only 8 receivers over the mean for the latter). Thus, results in Table 2 are calculated with two different ratio inhabitant/receiver, namely 0.9 for VBEB and 1.5 for EXP.

Table 2. Results of multiple values distributions - example

L_{DEN} *dB(A)*	*VBEB*	*EXP*
53	0.9	
56	1.7	
58	0.9	
60	0.9	
63	0.9	
64	0.9	1.5
66	1.7	3
69	1.7	3
70	2.6	4.5

By the above example, inhabitants exposed to levels over 65 dB(A) are 12 for the END method and only 6 according to the VBEB one. Thus, also estimated annoyance and corresponding action plans may differ according to each assessment method.

The procedures applied to the above example have also been used for the entire municipal territory of Pisa (about 90.000 inhabitants). Results show that distributions obtained by NEAR and VBEB methods are very similar, even though methods are very different. Moreover, these distributions have the same central value equal to that shown by the AVE method, but they are rather different from MIN and END. In addition, the results by EXP distribution are, as expected, intermediate between VBEB and END ones.

To analyse in more details the above differences, normal fits of the distributions were carried out and their goodness was evaluated by the Kolmogorov-Smirnov test. Even if not all fits pass this test, theoretical means are reliable and confirmed by mode values. Table 3 reports the model parameters, including D-statistic values to be compared with the critical value 0.0054 for level of confidence $\alpha = 0.01$. The normal models fit well only VBEB and AVE distributions. Table 3 shows also the population percentage within a standard deviation interval.

Table 3. Fits and data parameters of the distributions for the people noise exposure in Pisa

	END	*VBEB*	*EXP*	*AVE*	*MIN*	*NEAR*
Peak *	7.6	6.8	7.6	8.5	8.3	6.8
μ	60.0	55.7	58.6	55.9	51.2	55.5
σ	5.1	5.9	5.2	4.7	4.8	5.9
D-statistic	0.0142	0.0050	0.0077	0.0050	0.0134	0.0069
Mode	59	56	59	56	50	57
$\% \pm \sigma$	65%	70%	66%	71%	70%	69%

* percentage of population exposed to distribution central value

EXP and END show quite the same distribution: they overestimate exposure and they are sharper than normal model (as the MIN distribution). This shape effect seems to be due to considering a single value per building.

The observed difference between END and VBEB can be summarized into two facets: i) the choice of maximum level increases the central value; ii) considering all the receivers in the building exposed to the same noise level leads to a tighter and more irregular distribution. However, the NEAR method seems to reject the latter facet because it shows the same shape of VBEB even if all the receivers in the building are considered to be exposed to the same noise level. This contradiction could be explained considering that the nearest point is each time at a different distance between source and building. Thus, there is another random variable that enlarges the distribution. The similarity between VBEB and NEAR confirms the results obtained in [6]. The two methods produce the same results at large scale, but potentially give large differences locally.

Taking into account the above results, a crucial question arises: if official methods give different outcomes, which is the best to describe the people exposure? In answering this question, it has to be considered that estimation of noise levels and population assignment should have the same level of accuracy [4]. For our proposes, this means that we have to pay attention deriving too much detailed analysis on distribution methods without having reliable levels at receivers. Although maximum noise level has a small uncertainty, other receivers are more influenced by reflected sound and their accuracy may depend on calculated grid detail.

DIFFERENT RECEIVER CALCULATION METHODS: EFFECTS ON ESTIMATED EXPOSURE

Sound level uncertainty at receiver depends on calculation method. Two methods are available: i) interpolation of the calculated grid (the easiest); ii) calculation directly at the receiver (more accurate). The latter was not used for Pisa's mapping because isolevel curves were requested and direct calculation method requires too much calculation time. However, interpolation leads to include grid uncertainty and this could affect the plan of protection actions.

To highlights how results may vary with grid steps, a simplified scenario has been considered, formed by a single road and two buildings, each on the road side at the same distance from the road axis. Four grids have been used with the following steps: 10, 5, 2 and 1 m. In addition, different grid origins have been used. The results have been compared with those obtained by the direct calculation method and the differences increase for grid that are asymmetric to the source and for large steps. Such differences can be observed more clearly looking at ring points having maximum and minimum levels and computing their standard deviations as function of the grid spacing (Table 4).

Table 4. Standard deviations for receivers having maximum and minimum levels

Grid step	*1 m*	*2 m*	*5 m*	*10 m*
Standard deviation for maximum level	0.0	0.2	0.7	0.8
Standard deviation for minimum level	0.0	0.0	6.7	9.1

The maximum values have a small inaccuracy (less than 1 dB), whereas the minimum level varies up to 9 dB depending on grid origin. Thus, the estimation of the back-façade levels on a large area should be done only using a small step or by the direct calculation method.

The simplified scenario highlights also how the VBEB method, that takes into account all façades, applied for a large step grid overestimates back façade noise. These differences occur at low levels, usually at back façade, and similar results have been obtained for the entire municipal territory of Pisa.

EFFECTS OF CALCULATION METHODS ON ANNOYANCE AND ACTION PLANS

Noise effects on health may vary from annoyance (mood changes, working productivity loss, …) to serious consequences as the increase of myocardial infarction incidence. However, these effects become important above certain level of exposure and therefore it is necessary to identify percentage of people highly annoyed and protect them. There are many criteria to define a priority index for each zone to be protected. This assignment is also called noise scoring NS and the main methods are summarized in [8]. One of them is based on Miedema annoyance curves [9] estimating highly annoyed people percentage %HA per building according to equations (1) and (2):

$$\%HA = 9.87\cdot 10^{-4}(L_i-42)^3 - 1.44\cdot 10^{-2}(L_i-42)^2 + 0.51(L_i-42) \quad (1)$$

$$NS = \sum_i n_i \cdot \frac{\%HA}{100} \quad (2)$$

To plan mitigation measures the Italian law DM 29.11.2000 [10] has established an index calculated by a linear relation between actual levels Li and noise zoning limits L_{ref}:

$$NS = \sum_i n_i\left(L_i - L_{ref}\right) \quad (3)$$

The Miedema method does not need limits or reference values and it is health effect based. This method has also been improved [11] with correction factors for surroundings average levels, building absorption and quiet façades. Using only quiet façades correction factor and considering road traffic noise, a modified indicator according to relation (4) is obtained:

$$L'_{den,i} = L_{den,i} - 0.016\cdot\Delta Q_i\cdot L_{den,i} + 0.7\Delta Q_i \quad (4)$$

where ΔQ value is determined according equation (5):

$$\begin{cases}\Delta Q = \Delta L - 7 & if \quad \Delta Q < 20\\ 20 & if \quad \Delta Q \geq 20\end{cases} \quad (5)$$

in which ΔL is building levels span (difference between maximum and minimum values).

In Table 5 a comparison of %HA calculated with both grid and receiver methods (considering or not quiet façade correction) for the building reported in Figure 3 is shown.

Table 5. Highly Annoyed inhabitants for each method – example building in Figure 3

Method	*% of Highly Annoyed*	*N° of Highly Annoyed*
Direct with correction	12%	1
Direct	15%	2
Interpolated with correction	14%	2
Interpolated	16%	2

The number of people to be protected is generally greater using interpolation as it can be seen from average ratio between direct and interpolated methods of estimated %HA shown in Figure 4.

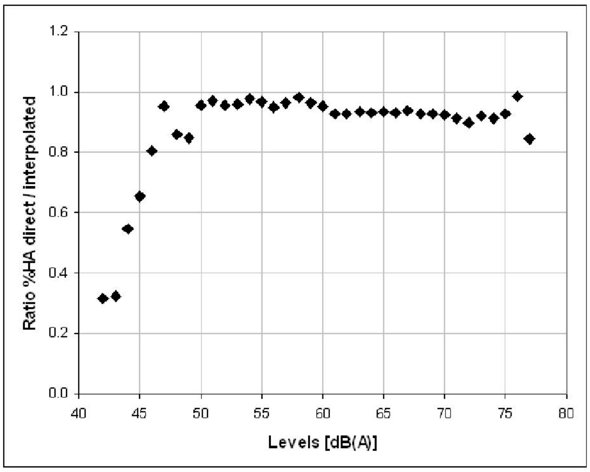

Figure 4. Influence of calculation methods on %HA

Moreover, correction for quiet façade can reduce the number of highly annoyed estimation: a decrease of about 8-14% inhabitants to be protected was observed all over the municipality. This could be significant in terms of resources especially noticing that greater differences occur at high levels.

The knowledge of the correct distribution of levels around the building helps to define priorities, to save funds and to use them in the most efficiently way. In fact, although highly annoyed percentage distribution over Pisa is relative quite low, varying from 8% to 9.5% according to the methods applied, if the direct calculation with quite façades correction is considered, then the number of highly annoyed inhabitants is reduced about 2200 units, which is not a negligible quantity.

CONCLUSIONS

This study has shown the influence of methodology in assessing the people exposure. Level distributions with accuracy not suitable for noise scoring method may lead to an incorrect evaluation and to less effective funding allocation.

The choice of the method must take into account the aim of the study, being the one oriented to epidemiological risk different from the one used to environmental noise information for the general public. Therefore, complexity and time spent for a method have to consider not only data availability but also the objectives.

This paper has also shown that VBEB method describes real exposure and it estimates annoyance better than the END method. However, it must be remind that it is reliable only with accurate levels distribution estimate, achievable by direct receiver calculation (small grid steps are generally not feasible). Instead, END method is the most suitable and practical for a first selection of risk zones that can be after refined using quiet façade correction. Moreover, this method is still the easiest to be understood by local administrations and it contributes to raise public awareness of noise problems.

By the end, before starting exposure estimation, it is crucial to take into account not only demographic data availability, but also level distribution method. It must be chosen according to the noise scoring indicator that have to be used to evaluate priorities.

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