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IMAGINE project: urban measurements of Lden and Lnight and calculation of the associated uncertainties.

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ABSTRACT

This article describes the principles of the new measurement method developed within the IMAGINE European project to determine L_{den} and L_{night}, as defined by the European Noise Directive 2002/49/EC, by direct measurement of the noise levels. The measurement method was tested in a real and complex urban environment including a major road, a major railway line and an industrial site. A description is given for the calculation of the yearly averaged levels and the uncertainty estimation. Concerning such long term indicators, estimation of uncertainty is a rather complex task, especially if the yearly L_{den} and L_{night} are derived from measurements performed over a short period of the year. The uncertainties concern the microphone position, the source variation, the meteorological variations, the correction for background noise and the sound level meter class 1 uncertainty. The example described here is based on a measurement campaign performed over one year in the city of Pisa (Italy).The aforementioned measurements would be typically applied to support the credibility of noise map calculations towards the citizens and to validate calculations of noise maps in well-defined situations.

INTRODUCTION

Following the requirements of the Environmental Noise Directive 2002/49/EC (END) [1], noise levels are to be mapped in Europe. The metrics used by this European Directive are L_{den} and L_{night}: In the END it is stated that L_{den} and L_{night} can be either computed or measured. Therefore, within the European IMAGINE project [2] work has been performed to produce a protocol to measure these two values, representative of the average year, as defined in the END. A lot of effort has been spent to give not only a framework for the measurement of the two indicators L_{den} and L_{night}, but also to attribute an overall uncertainty so that, depending on the method used to perform the measurement, it could be stated how accurate that value is. A concrete example is given concerning the noise measurements performed of a major road, however far from the road itself and in a complex urban environment.

BASIC PRINCIPLES

The method to measure the European noise indicators L_{den} and L_{night}, makes it possible to separate the assessment of the source variation and its uncertainty on one hand and the transfer function between the source and the receiver under different propagation conditions, which depends on the meteorological parameters, and its uncertainty on the other hand.

The general equations described in the END are used to calculate the L_{den} and L_{night} during each combination of source and propagation condition. Source and propagation are grouped in classes defined by level intervals that are specified by the team performing the measurement. The choice of the intervals depends on the variability of the source and the propagation conditions as well as on the possibility to have a large or a small amount of samples (generally L_{pA}) to use for the evaluation. Once a combination of these intervals is set, L_{den} and L_{night} can be calculated averaging the levels recorded during these combinations.

Uncertainties are then associated with the overall long-term noise value obtained, by integrating the several separate short-term measurements and related uncertainties used to extrapolate the yearly average L_{den} and L_{night}. The method developed follows the requirements of the GUM [3], which states that each significant source of error has to be identified and corrected for. The basic principle is that, if the quantity L_m is measured, which is a function of the quantities x_j, then:

$$L_m = f(x_j) \qquad \text{(Eq. 1)}$$

If each quantity x_j has the standard uncertainty σ_j the combined uncertainty is given by:

$$\sigma(L_m) = \sqrt{\sum_1^n \left(c_j \sigma_j\right)^2} \qquad \text{(Eq. 2)}$$

where the sensitivity coefficient c_j is given by:

$$c_j = \frac{\partial f}{\partial x_j} \qquad \text{(Eq. 3)}$$

The measurement uncertainty to be reported is the combined measurement uncertainty associated with a chosen coverage probability. By convention, a coverage probability of 95% is usually chosen, with an associated coverage factor of 2. This means that the reported measurement uncertainty becomes L_m+2σ.

For environmental noise measurements $f(x_j)$ is complicated and it is hardly feasible to formulate exact equations for the function f. The calculation of uncertainty correlated to each parameter could be in any case performed following the approach suggested by Kephalopoulos et.al. [4] where it is explained how noise levels could be associated to their corresponding uncertainties. Hence, in the following, it is necessary simplifications to be made. Following the principles given in ISO 3745 [5], some important error sources could be identified:

$$L_{true} = L_m + \delta_{slm} + \delta_{sou} + \delta_{met} + \delta_{loc} + \delta_{res} \qquad \text{(Eq. 4)}$$

where L_{true} is the true (no errors) value during the specified conditions for which we want a measured value, L_{m} is the measured value, δ_{slm} is the error of the measurement chain (sound level meter in the simplest case), δ_{sou} is the error due to deviations from the ideal operating conditions of the source, δ_{met} is the error due to meteorological conditions deviating from the ideal conditions, δ_{loc} is the error due to the selection of receiver position and δ_{res} is the error due to residual noise.

Equation (4) is very simplified and each source of error is a function of several other sources of error. In principle Eq. (4) could be applied on any measurement lasting from seconds to years. In [6] the measurements are divided into short and long-term measurements. A short-term measurement may typically range between 10 minutes and a few hours whereas a typical long-term measurement may range between a month and a year.

In many cases the measurement results should be manipulated to extrapolate them to other conditions, e.g., normalizing to different traffic flows, and to use them for calculating quantities like the L_{den}. Let us consider the following specific case.

In this L_n denotes the L_{pA} for condition n, which lasts for p_n of the total time, whereas L . denotes the total L_{pA} for the overall time interval. We then get:

$$L = 10\lg\left(p_1 10^{L_1/10} + p_2 10^{L_2/10} + \ldots + p_n 10^{L_n/10}\right) \qquad \text{(Eq. 5)}$$

If $L_1,..,L_n$ are independent the sensitivity coefficient c_1 is then given by

$$c_{Lj} = \frac{\partial L}{\partial L_j} = 10\lg(e)\frac{p_j \cdot 10^{L_j/10}\ln(10)\cdot 0{,}1}{p_1 10^{L_1/10} + p_2 10^{L_2/10} + \ldots\ldots + p_n 10^{L_n/10}} = \frac{p_j 10^{L_j/10}}{\sum p_i 10^{L_i/10}} \qquad \text{(Eq. 6)}$$

As $\sum p_i = 1$ these coefficients are not independent. Instead we write Eq. (5) in the form

$$L = 10\lg\left(p_1 10^{L_1/10} + p_2 10^{L_2/10} + \ldots + p_{n-1} 10^{L_{n-1}/10} + (1 - \sum_{i=1}^{n-1} p_i) 10^{L_n/10} \right) \quad \text{(Eq. 7)}$$

For c_{pi} we get

$$c_{pi} = \frac{\partial L}{\partial p_i} = 10\lg(e) \frac{10^{L_n/10} - 10^{L_i/10}}{\sum p_i 10^{L_i/10}} \quad \text{(Eq. 8)}$$

L_i is determined with the standard uncertainty u_{Li} and p_i with the standard uncertainty u_{pi}. The standard uncertainty u of L is then given by

$$u = \sqrt{\sum_{i=1}^{n} \left| \frac{\partial L}{\partial L_i} \right|^2 u_{L_i}^2 + \sum_{i=1}^{n-1} \left| \frac{\partial L}{\partial p_i} \right|^2 u_{pi}^2} \quad \text{(Eq. 9)}$$

where the letter u instead of σ is used to specify that these uncertainties are estimated uncertainties.

EXAMPLE OF UNCERTAINTY CALCULATION

Major road noise source

The method developed, is based on the aforementioned rules for the uncertainty calculation, and was tested on an assessment position located in a complex urban environment. The location was about 150 m away from a major road in which were circulating more than three million vehicles per year. The microphone at the assessment point was placed at 4m height and 2m away from the flat façade of a house.

At this location, several other noise sources were most of the time simultaneously present (e.g., fan noise of a nearby industrial plan, railway, local road, aircraft, people talking), having, when active, approximately the same instantaneous L_{eq} as the specific source under assessment. It was therefore necessary to discriminate the contribution of the major road, and evaluate the uncertainty of the overall measurement performed. The noise from the major road was measured to check the traffic variations during the day, the week and the year. Two methods were used to quantify the traffic along the major road: the first by direct counting and classification of the vehicle pass-bys and the second by assessing the L_{95} value using a microphone placed close to the road.

Meteo classes

The following meteorological conditions were measured: wind direction, wind speed, temperature, temperature gradient, T*, u*, 1/L (inverse Monin-Obuchov length) gradient. Based on these measurements and also following the definition of meteorological classes relevant for noise propagation developed in the HARMONOISE project [7], four meteorological classes representative of the possible propagation conditions were established. These classes varying between class M1 for stable meteorological conditions with favourable sound propagation and class M4 for very unstable meteorological conditions with unfavourable sound propagation. It is essential to underline the fact that an assumption for the meteo classes was made. Having measured the meteo classes over more than four months, and for one month each season of the year, the information about this subset of the meteo classes used was assumed to be representative for the whole given year.

To get the uncertainty due to the propagation conditions, four possible meteorological situations were distinguished, depending on the curvature of the sound propagation. About twenty different $L_{pA,i,source}$ were compared to the corresponding $L_{pA,i,receiver}$ and, based on these measurements, the following meteo uncertainties were derived (Table 1).

In the Table 1, class M1 corresponds to the more favourable propagating condition whereas, class M4 to the unfavourable. Since the environment considered in this study was an urban environment, free field meteo conditions were indeed not even closely related to the local meteo conditions between the buildings and above these [8]. The uncertainty values calculated confirmed this hypothesis, since all values were between 1.3 dB and 2.1 dB despite of the fact that in general stable meteo conditions (class 1 in this study) should relate to a low uncertainty whereas unstable meteo condition (class 4 in this study) should relate to a large uncertainty.

Table 1. Uncertainties associated to meteo variation for each meteo class (M1, M2, M3, M4).

Class	M1	M2	M3	M4
σ_{met}	1.5	2.0	2.1	1.3

The meteo classes were then averaged during the period investigated. Considering the distribution of the samples (e.g., taking samples every day between 2:00 am and 3:00 am, after one month there were 28 samples distributed between M1, M2, M3 and M4), the uncertainty concerning the determination of the meteorological classes distribution could be found using the formula of (Eq. 2).

Operating condition classes

To extrapolate the noise contribution of the road, at first a classification of the road traffic was performed by monitoring the road traffic over 48h. This obviously introduced an uncertainty, since the extrapolation to the annual average traffic from different hourly time intervals should be estimated. To partially cope with this, the L_{95} level was used as an indicator of the variation of the road traffic along the year. In other words, the traffic was monitored using a microphone, then the L_{95} was used as a rough estimation of the presence of vehicles. Using several 15min samples of the L_{95}, there was a sufficient number of elements to perform a statistical evaluation of the traffic conditions during several moments of the day, during different days of the week and during different seasons of the year, which could then be used to determine a σ for the road traffic flow fluctuations. Five classes of traffic flow during a single day were identified, and regarded as “A” or “B” during the “day”, and as “C”, “D”, “E” during the “night”.

Using the first technique (direct counting of vehicles) no information is available on the traffic volumes during other days than the one used for the assessment, however, counting vehicles is necessary to know which is the expected uncertainty due to the specific types of vehicles during the specific moment of the short-term measurement. In other words, if only noise levels are recorded, there is no information whether or not these levels are caused by the average vehicle pass bys or by a specific combination of “acoustically exceptional” vehicles. Therefore, not only several levels are to be measured to calculate the noise levels at the assessment position, but also the number of vehicles during each recorded short-term L_{pA}. For the situation investigated, calculations were based on 15 min L_{pA} records. In all different periods subsequent samples were used to evaluate the uncertainty considering the number of vehicles each 15 min, resulting in a selection of five different classes (Table 2):

Table 2. Uncertainties associated with source variation for each traffic class.

	A	B	C	D	E
σ_{sou}	0.5	0.5	0.8	1.0	1.9

This uncertainty is to be used if the traffic flow is measured directly, or taken from local authority statistics, and the extrapolation of the L_{den} is performed based on these numbers of vehicles and traffic distributions.

The same procedure was applied to estimate uncertainties coming not only from A, B, C, D, E classes for one single day of a week, but also from classes which take into consideration monthly or seasonal variations by integrating the different traffic flows during the rest of the weekdays, Saturdays, Sundays, and, on a two season (summer and winter time) basis. Once again, these could directly be assessed on the basis of the L_{pA} noise levels recorded in each period. In other words, over the weeks the noise measurements performed (e.g., one in September 2005, one in December 2005, two in February 2006, and one in June 2006) to assess the road traffic noise source, the L_{pA} were recorded for each A, B, C, D, E period, each day (therefore, 5 L_{pA} every day). Over such periods the uncertainty is calculated based on the several i-th day samples (e.g., 9 weekdays implies 9 samples -Mon, Tue, Wed, etc.).

Extrapolation at the receiver by means of measured transfer functions

In the situation investigated, local noises were present, such as cars passing by the local road, people chatting, birds singing, besides the presence of three other major environmental noise sources (major railway line, industrial source, major airport). To evaluate the contribution to the overall noise levels of the road traffic only, a transfer function between the major noise source and the receiver was estimated under several meteorological classes. Based on the transfer function it was possible to use only the noise records (noise levels) when the noise source under assessment (i.e., road traffic) was clearly distinguished from other noise sources. Besides estimating the transfer function, a correction should nevertheless be made for the residual noise at the receiver, since recording a “clearly distinguished” noise did not necessarily mean having it more than 10 dB (as typically considered in measurements) louder than all the other noise sources present at the same time.

What was regarded in other standards as background noise or extraneous noise or residual noise was all regarded here as residual noise. Residual noise is the noise produced by all sources but the specific source under assessment. Residual noise could therefore be considered a local noise occasionally produced, another relevant main noise source, or a frequent non-environmental noise source (e.g., people chatting, birds singing).

Since the short-term periods used in this study were selected during a time period when no other noise sources (such as railway, local road, aircraft, people, birds) were present, in the time period used for the assessment, the residual noise was limited only to the fan from the nearby industrial plan. This fan noise was previously measured to be $L_{pA,res}$= 43.5 dB and it was a constant source. Since the road traffic noise had an L'_{pA} no more than 10dB higher than the L_{pA} of the fan (=L_{res}), the correction for residual noise should be used then. Therefore, the following formula should be used:

$$L = 10 \cdot \log_{10}\left(10^{L'/10} - 10^{L_{res}/10}\right) \qquad \text{(Eq. 10)}$$

Subsequently, uncertainty was calculated over the transfer function for each meteo class, and the residual noise uncertainty was also considered. This latter uncertainty was derived using the formula

$$c_{res} = \frac{-10^{-(L'-L_{res})/10}}{1-10^{-(L'-L_{res})/10}} \qquad \text{(Eq. 11)}$$

At the assessment position, the average $_{LpA}$ was L’= 49.0 dB, whereas $_{LpA,res}$= 43.5 dB, hence, the sensitivity coefficient is c_L=c_{res}= 0.38.

Other specific uncertainties

The distance between the source and the receiver was about 250 m, therefore the uncertainty of atmospheric absorption was also considered (although it was expected to be very low) and assumed to be 0.2 dB.

For the sound level meters used (one at the receiver point, and one at the road side), the uncertainty attributed was u_{slm}=0.5 dB for each microphone.

The residual noise at the road was about 30 dB(A) lower than the road traffic noise, therefore no correction was needed and the uncertainty of the residual noise was set u_{res}=0 dB.

Because of the position 2m in front of a façade, the uncertainty was taken as u_{pos}=0.5 dB as derived from a study, performed in the context of the IMAGINE project, to test the acoustical corrections for reflections on a façade [9].

Calculation of the overall uncertainty

Basically, the sensitivity coefficients were calculated using the formula (Eq. 6), since the noise levels used were independent values.

Subsequently, the formula (Eq. 7) should be applied iteratively: the first time, while averaging over the day, evening and night, then while averaging for the day of the week, then while averaging for the seasons and finally while calculating the L_{den} using the three periods (day, evening, night).

It should be noted that u_{sou} and u_{met} are then included in the calculation of u_{den}. For the measurement campaign in this study, this was found to be 0.7 dB (u_{den} is not the overall uncertainty).

Once all the uncertainties were calculated, for this specific situation, the overall uncertainty was:

$$u = \sqrt{{u_{den}}^2 + {c_{res}}^2 {u_{res}}^2 + {u_{pos}}^2 + {u_{slm1}}^2 + {u_{slm2}}^2 + {u_{atm}}^2} \qquad \text{(Eq. 12)}$$

and, after substituting with the values, we get u = 1.2 dB.

CONCLUSIONS

In the present article the method developed for the testing of the protocol concerning the measurement of L_{den} and L_{night} following the requirements of the END was presented, in the case of road noise source measurements. Specifically, it was shown how it is possible to measure the required values in complex situations, obtaining both the required noise levels and the associated uncertainties. Once this accomplished, the results are satisfactory for communicating them to the population exposed as well as to the policy makers who need to implement noise reducing measures where appropriate. In the past the measurements performed were often either including extraneous noise sources, or only one source, however this measurement was representative only of a partial period of the year. The technique described here ensures that long term noise values for a selected specific source could be obtained in any complex situation which includes periodical variations and coexistence of other noise sources, together with a statistically robust evaluation of the uncertainty associated to the value calculated. In the past, often complains were arising from the consideration that the measurement performed was not necessarily representative of a long term period close to the true yearly average. Adopting in an international noise measurement standard which might be similar to the one described by Jonasson [6], the principle of delivering an uncertainty associated to any measurement performed to evaluate the L_{den} and L_{night} indicators, can be clearly considered as an improvement, since this way is always possible, e.g. to state that a certain L_{den} and L_{night} "*is with 95% confidence not more than the given L_{den}+2u and L_{night}+2u values*". Also, in view of the noise mapping of the major European cities, it will be possible to demonstrate to the population as well as to the local authorities that the computed noise levels are a correct estimation of the real value of L_{den} and L_{night}, by performing just a few measurements over short time periods in urban areas. Further implementation of these principles in future noise measurements will contribute to the extensive testing and eventual final acceptance of these procedures by the international noise measurement standards.

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