Adopting bootstrap for the uncertainty estimation of road traffic noise measurement

Consolatina Liguori, Antonio Pietrosanto, Alessandro Ruggiero, Domenico Russo, Paolo Sommella
Department of Industrial Engineering (DIIn)
University of Salerno
Fisciano (SA), Italy
tliguori@unisa.it; apietrosanto@unisa.it; ruggiero@unisa.it; drusso@unisa.it; psommella@unisa.it

***Abstract*— In the context of noise pollution, this paper aims to demonstrate the importance of uncertainty evaluation in the environmental noise measurement focusing the attention on the variability of the measurand. Managing the result of a comparison between measured value and the maximum levels permitted in law does not involve a straightforward comparison of values, given that such measurement, which can only be an approximation of the value of the measurand, is expressed as an interval. Consequently, it is essential to take into account the uncertainty associated with the measurement. Attention is focused on the variability of the measurand as a source of uncertainty and a procedure for the evaluation of uncertainty for environmental noise measurement is proposed. Drawing on real traffic noise dataset, the contribution of measurand variability on measurement uncertainty is determined by using the bootstrap method. Experimental results exploring the adoption of the proposed method confirm the reliability of the proposal. It is shown to be very promising with regard to the prediction of expected values and uncertainty of environmental noise when a reduced dataset is considered.**

***Index Terms*— noise control; measurement uncertainty; measurement time interval; statistical analysis; bootstrap method.**

I. Introduction

Nowadays the noise is considered the most significant health hazard to the working population referring to the number of people affected [1]. In Italy, the current legislation mainly focuses around the maximum acceptable limits in terms of the A-weighting equivalent level of environmental noise:

$$L_{Aeq} = 10\,\mathrm{Log}\frac{1}{T}\int_{T}\left[\frac{p_A(t)}{p_{rif}}\right]^2 \mathrm{d}\,t \qquad (1)$$

which indicates the level of a continuous stationary noise having the same acoustic energy content of the floating noise under measurement compared to the average sensitivity curve in terms of frequency of the human auditory system.

The management of the result of a comparison between a measured value and a legal threshold is a complex matter. Many decision-making processes are based on the outcomes of these comparisons, which may have implications not only from an economic point of view, but also on environmental and / or social matters. The problem stems from the comparison between a measured quantity and a threshold value not being possible through a simple mathematical comparison between the two values given that it must take into account the uncertainty associated with the measurement. The task of establishing the decision-making rules to test the compliance of a product to specifications, taking into account the uncertainty of the measurement [2],[3]. For all these reasons, it is essential to take into account the uncertainties associated with the measurement, as reported for international technical standards [4], because uncertainties are a quantitative indication of the reliability of the result. Any measurement certification has to adhere to this standard.

With reference to environmental measurements, exceeding thresholds may cause health risks and then it becomes essential to find the relationship between measurement uncertainty and acceptable social risk [5]-[8]. The eventual aim of the research described in this paper is the realization of an advanced system for the environmental acoustic monitoring and for the real-time assessment of uncertainty associated with measured levels.

In order to evaluate compliance with near limit values it is necessary to establish some rules: simple acceptance and simple rejection rules are the most basic. The first establishes that the result of a measurement is compliant if it falls within the specification zone (Fig. 1: cases 1 and 2) while the second establishes non-compliance if a result of a measurement falls outside the specification zone (Fig. 1: cases 3 and 4).

In the field of environmental acoustics, the choice of decision rules depends on the purpose of the evaluation.

In particular, to protect the receiver, stringent acceptance + relaxed rejection rule (Fig. 2) is chosen, in which the stringent acceptance rule states that the result is compliant if the entire measurement including the confidence zone lies within the specification zone (Fig. 2: case 1) and the relaxed rejection rule states that the result of a measurement is not

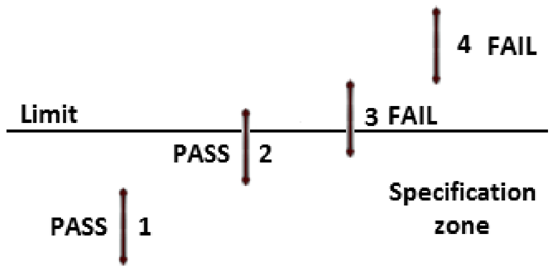

Fig. 1. Simple acceptance and simple rejection rules

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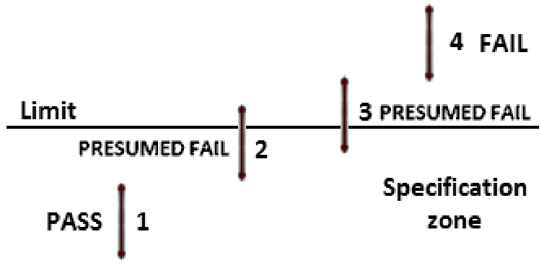

Fig. 2. Stringent acceptance + relaxed rejection

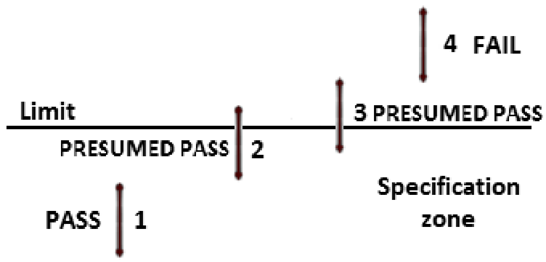

Fig. 3. Relaxed acceptance + stringent rejection

compliant if it is outside the specification zone with all the confidence zone (Fig. 2: cases 2,3,4).

In order to protect the source, relaxed acceptance + stringent rejection rule (Fig. 3) is chosen [9], in which the relaxed acceptance rule states that the result of a measurement is compliant if it is not outside the specification zone including the confidence zone (Fig. 3: cases 1, 2, 3) and the stringent rejection rule only considers non-compliance for those measurement that fall entirely outside the specification zone including allowance for the confidence zone (Fig. 3: case 4).

In any case, in order to evaluate the reliability of the decision, it becomes essential to associate the uncertainty with the measured value. Nowadays, an adequate technical and procedural reference standard has not been yet available.

II. State of the Art

In recent years, there has been considerable interest amongst the scientific community and experts in the field of acoustics about the quantification of environmental noise measurement uncertainties [10]-[12]. In particular, there has been an analysis of possible sources of uncertainties associated in this area i.e. characteristics of measurement instrumentation [13], [14], variability of the measurement conditions [15], [16] and instrumentation calibration [17].

An example of application of the Guide to the Expression of Uncertainty in Measurement (GUM), which involves statistical evaluation and consideration of the technical specifications of the instrumentation and of the technical standards on electro-acoustics, is the uncertainty estimation of a class 1 sound level meter. With reference to a generic stationary outdoor source, it is estimated that value that takes into account the inherent uncertainty contributions, that is the deviation from the nominal value, i.e. weather conditions (temperature, humidity, pressure), linearity, A weighting curve, microphone isotropy, but which does not take into account the positioning of the measuring instruments, is about 0.49 dB. The global uncertainty, assuming that its components are uncorrelated, can be expressed as:

$$u(L_{Aeq}) = \sqrt{u_{instrum}^2 + u_{dist}^2 + u_{refl}^2 + u_{height}^2} \quad (2)$$

where:

- i_{nstrum} is the uncertainty associated to the measurement instrumentation [dB];
- u_{dist} is the standard uncertainty associated to the distance between source and receiver [dB];
- u_{refl} is the standard uncertainty associated to the distance of microphone from reflective walls [dB];
- u_{height} is the standard uncertainty associated to the height of the microphone above the ground [dB].

However, to provide an adequate estimation of total uncertainty associated with the measurement of the equivalent level of environmental noise, the intrinsic variability of the measurand cannot be ignored.

In literature, for the estimation of the uncertainty associated with the inherent variability of environmental noise, studies are usually performed assuming a normal distribution for the originating population [18], but this hypothesis is difficult to be accepted [19]-[22], so several authors, such as Batko and Stępień [23] analysed the uncertainty of the noise indicators using a statistical resampling technique does not have limitations in terms of form and properties of considered statistics: the bootstrap method.

III. Proposed Methodology and Experimental Data

Measurement data were collected by using the Sound Level Meter Larson Davis 831, Class 1 Environmental Noise & Building Acoustics Analyzer, placed on the side of A3 motorway near Salerno (Italy), at a distance of 1 m from the roadside at a height of 4 m. Main parameters of the noise source, recorded during the measurement campaign, are reported in Table I.

Data collection was performed during one week (wind speed less than 5 m/second and no rain) from Friday 10:00.00 p.m to (next) Friday 09:59.59 p.m. In details, the time history logging step (T_{const}) was fixed at one second. To highlight the cyclical behavior observed during the week, the equivalent sound pressure level $L_{Aeq,1h}$ (resulting from a sliding time window of one hour) has been reported in Fig. 4 according to

TABLE I. Main Parameters Of Road Traffic

	Average hourly traffic volume		**Mean Speed**	
	Light vehicles	**Heavy vehicles**	**Light vehicles**	**Heavy vehicles**
Diurnal reference time (6-22 hr)	172 veh/h	62 veh/h	113 km/h	93 km/h
Nocturnal reference time (22-06 hr)	30 veh/h	25 veh/h	109 km/h	91 km/h

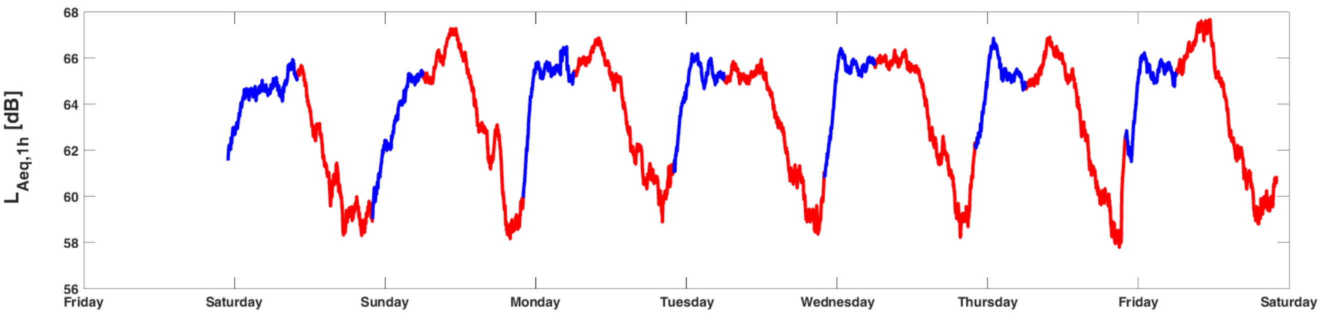

Fig. 4. Equivalent sound pressure level $L_{Aeq,1h}$ during the measurement campaign (red line: diurnal reference time; blue line: nocturnal reference time).

different colors (red and blue) corresponding respectively to the diurnal and nocturnal reference time.

In order to verify the approach proposed for the measurement uncertainty estimation against the range of the equivalent sound pressure level, focus has been devoted to the observation periods characterized by the lowest and greatest values, namely 1-hour data collections starting on Thursday at 8:00.00 p.m. and on Friday at 9:00.00 a.m. respectively.

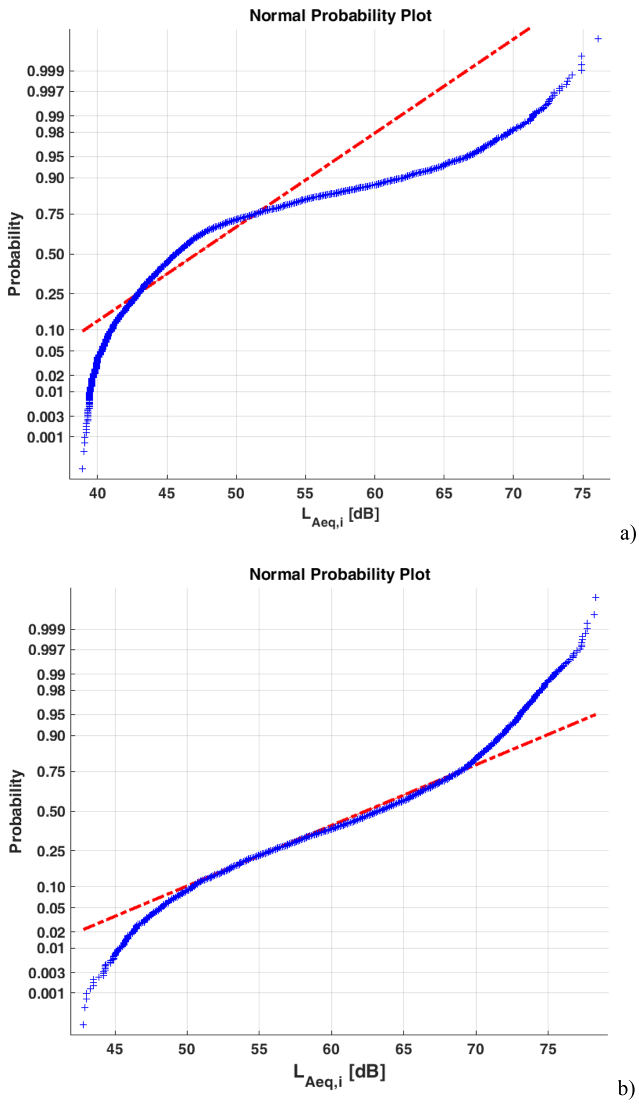

Fig. 5. Normal probability plot of the sound pressure level for 1 hour data collection:
a) start on Thursday at 8:00.00 p.m. ; b) start on Friday at 9:00.00 a.m.

Several normality test (the Shapiro-Wilk test, the Jarque-Bera test, the Lilliefors test, the Kolmogorov-Smirnov test and the Anderson-Darling test) have been performed on real data obtained from road traffic noise measurement: the results reported in Fig. 5 (in terms of the normal probability plots of the sound pressure levels measured during both the observation periods) show the examined population is not strictly Gaussian.

From all so far reported, the authors suggest to determine the uncertainty associated with the inherent variability of road traffic noise using the normal bootstrap method, because it is a computationally intensive statistical technique that allows one to make inferences from data without making strong distributional assumptions about the statistic that is calculated and/or the data [24].

The main idea is that a number of new data sets, which are referred to as bootstrap samples, can be generated from the initial data set by sampling with replacement. With this resampling scheme, these distributions can be seen as approximations to the true distributions of the estimators, and then a good estimate can be obtained of the distribution of a statistics of interest, such as bias, standard deviation and so on [25].

The algorithm of the expected value and standard uncertainty of the noise indicators performed by the normal bootstrap method is shown in Fig.6.

The results of the proposed approach may be compared with the estimation of the expected value for the noise indicator and of the corresponding uncertainty using the classical method (according to [4]). In detail, the expected value of the equivalent sound pressure level (referring to the measurement time) - in the classical approach - is determined by eq. (3):

$$\bar{L}_{AeqTmeas} = 10\log\left(\frac{1}{n}\sum_{1=1}^{n} 10^{0,1\,L_{Aeqi}}\right) \qquad (3)$$

where n is the size of the considered sample.

The corresponding standard uncertainty is determined by eq. (4):

$$u(\bar{L}_{AeqTmeas}) = \sqrt{\frac{\sum_{i=1}^{n}\left(L_{Aeqi} - \bar{L}_{AeqTmeas}\right)^2}{n(n-1)}} \qquad (4)$$

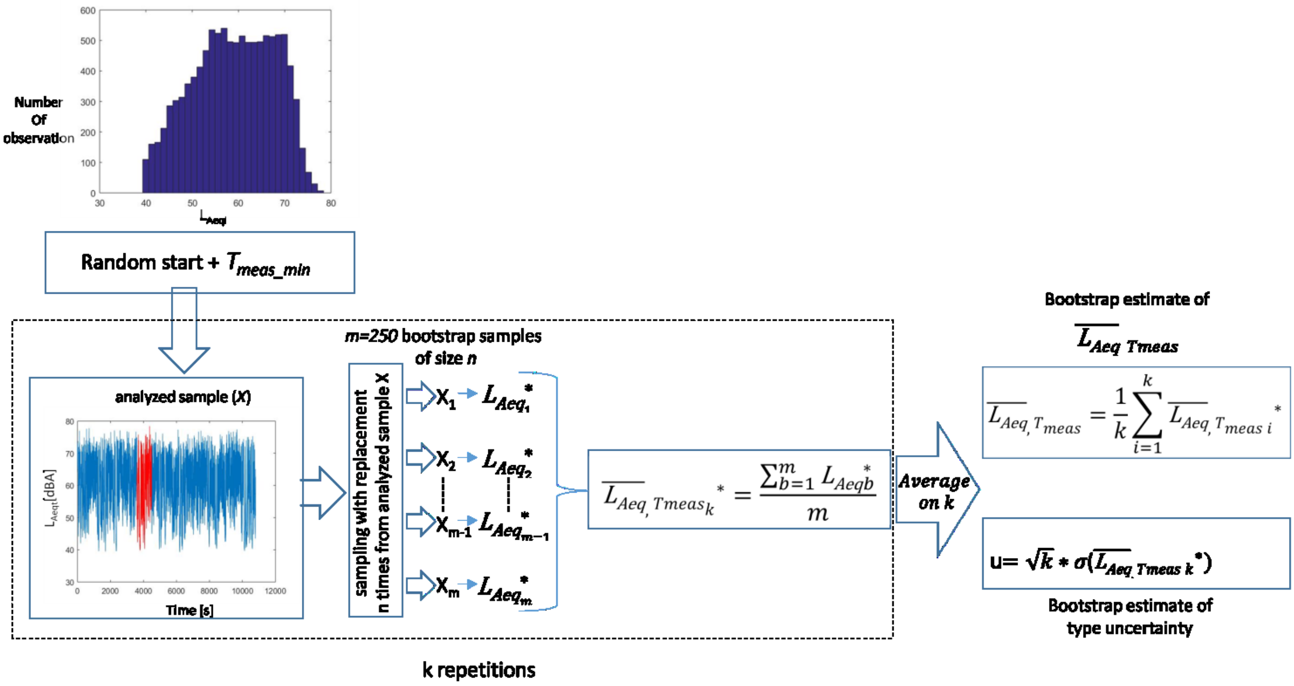

Fig. 6. Estimation of expected value and standard uncertainty according to the bootstrap approach

The calculation scheme according to the classical approach is depicted in Fig. 7.

Both the bootstrap and classical approaches have been adopted for estimating the measurement uncertainty of the equivalent sound pressure level about the observation periods previously introduced. In details, for each 1-hour data collection, the procedure disclosed in [26] has been applied to detect a minimum time interval as a randomly selected short episode (including n measured samples) well representative of the observation period (see Fig.8-9).

Table II summarizes the comparison results when the classical and bootstrap approaches are applied to the acquired datasets (both for the minimum measurement time interval and the whole observation period).

In details, about the application of the bootstrap approach, the expected value and standard uncertainty of the equivalent sound pressure level are achieved by considering $m = 250$ bootstrap samples and by averaging the corresponding results on k = 100 repetitions (in order to reduce the influence of the random sampling from the population).

Generally speaking, the bootstrap approach allows for estimation of the equivalent sound pressure level with better precision (smaller measurement standard uncertainty) than the results by the classical approach. As may be noted, both the classical and proposed methods lead to a very good estimation of the expected value for the short-term noise indicator when a reduced number of samples are considered. Nevertheless, the reduced sample size introduces an overestimation of the true

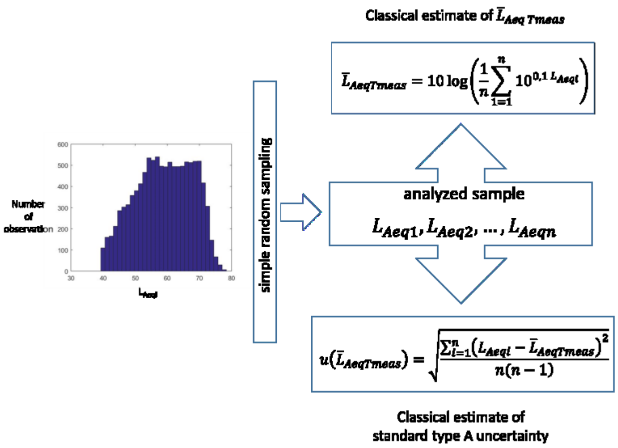

Fig. 7. Estimation of expected value and standard uncertainty according to the classical method.

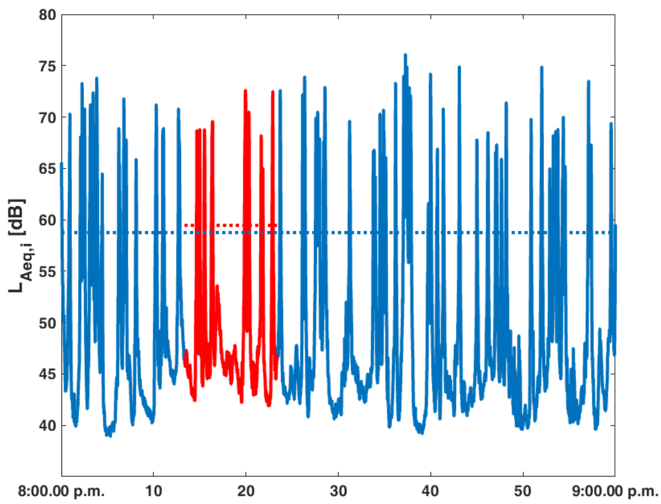

Fig. 8. Sound pressure levels and equivalent indicator for first observation period (solid and dotted blue lines); minimum measurement time interval and corresponding equivalent sound pressure level (solid and dotted red lines).

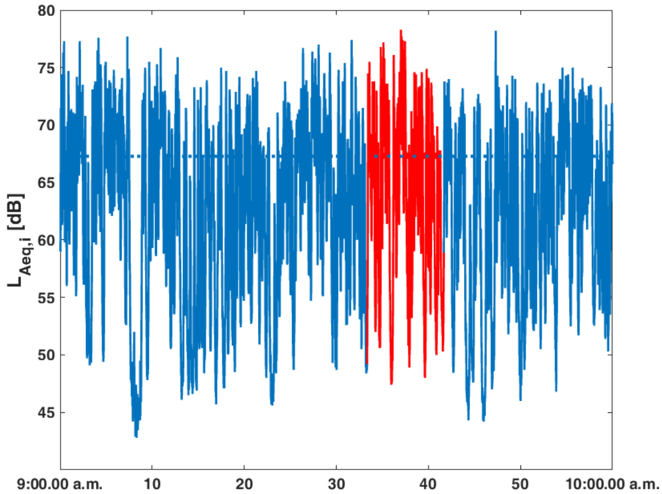

Fig. 9. Sound pressure levels and equivalent indicator for second observation period (solid and dotted blue lines); minimum measurement time interval and corresponding equivalent sound pressure level (solid and dotted red lines).

standard uncertainty, that is more evident with the classical method (particularly for the evening time episode).

V. Conclusions

In this paper, the contribution of the environmental noise variability on equivalent sound pressure level measurement uncertainty is explored. The proposal, based on normal bootstrap method, has been experimentally verified with real data obtained from road traffic noise measurement. On the basis of the results analysis, this procedure has been revealed to be effective both for the prediction of noise levels and for the corresponding uncertainties characterizing large time intervals by measuring only a short time window of the acoustic phenomena. Further research will be addressed to the suitable upgrading of the firmware for sound level meter in order to enhance the traditional functions of the instrument with the automatic real-time evaluation of inherent measurement uncertainty contribution.

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TABLE II. Comparison of Bootstrap and Classical Methods for Uncertainty Estimation

		Bootstrap Method		Classical Method			
		Measurement time interval		Measurement time interval		Observation period	
	Sample size (n)	Expected Value [dB]	Uncertainty [dB]	Expected Value [dB]	Uncertainty [dB]	Expected Value [dB]	Uncertainty [dB]
Morning Time (09-10 a.m.)	500	67.33	0.19	67.35	0.20	67.29	0.16
Evening Time (08-09 p.m.)	600	59.46	0.25	59.50	0.30	58.75	0.22

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