inter.noise 2025
SAO PAULO - BRAZIL
24 • 27 AUGUST

# Extending the partial equivalent sound pressure level model to manage residual sound and exclude unwanted events identified with artificial intelligence

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## ABSTRACT

*Unwanted events, residual sound and irrelevant sounds affect the quality of measurement results obtained by long-term noise monitoring. Previous studies have shown that irrelevant sounds can be identified with direction-of-arrival techniques, which allow using corrected data in a model called partial equivalent sound pressure level. Under given assumptions, the model can also account for residual sound. Other studies have shown that artificial intelligence can be used to automatically identify unwanted events in noise monitoring measurements. In this paper, we extend the partial equivalent sound pressure level model by correcting for unwanted events, in addition to the previously included corrections for residual sound and irrelevant sounds. The proposed extended model is applied to a case study, which is presented together with a discussion of the assumptions made and the limitations of the method. We compare the results with those achieved by applying the methods given in ISO 1996-2. Our primary hypothesis is that better estimates of equivalent sound pressure levels can be achieved, but other factors such as the efficiency and reliability of the extended model are also analyzed. Finally, further work towards a generalization of the method is mentioned.*

## 1. INTRODUCTION

Performing unattended equivalent sound pressure level measurements of urban sound sources can be a challenging task when other sound sources are active simultaneously. In such complex scenarios, the contributions from the non-relevant sound sources must be managed in order to minimize their effect on the measurement results. Standardized methods for managing these contributions, once they have been identified, are given in ISO 1996-2 [1]. Traditional methods used to identify the contributions can be time-consuming, requiring hours of listening to recorded material. This imposes economic strains on projects and stakeholders who need to demonstrate compliance with noise limits such as construction sites, transportation (roads, railways and airports), harbors, racetracks, shooting grounds and industries, among others.

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In this paper, we explore how technological developments seen in recent years can be effectively implemented to automate the management processes efficiently and reliably, focusing on artificial intelligence (AI) and sound source identification in the context of environmental noise measurements. Our methodology extends the previously presented concept of partial equivalent sound pressure level or $PL_{eq,T}$ [2 - 4].

The following commercial implementations from the company Norsonic are used throughout the paper: Noise Compass [5] for identification of the direction of arrival of incoming sounds, NoiseTag [6] for identification of unwanted events with artificial intelligence, and NorCloud [7] as platform for data management. It must be noted that the developed methodology and analysis can be extended to other tools exploiting similar technology [8 - 12] and we therefore aim at the generality of the processes presented.

## 2. METHODOLOGY

In this section, we revisit the model for partial equivalent sound pressure level, $PL_{eq,T}$, and we introduce the methodology used to estimate its components. We also explain the method from ISO 1996-2 used in the comparison of results.

### 2.1. Model for $PL_{eq,T}$

The model for $PL_{eq,T}$ has been introduced elsewhere [2 - 4], but the basic concept is repeated here for completeness.

Considering a complex urban sound scenario where multiple sound sources are active simultaneously but only one, or some of them, are of interest, the measured equivalent sound pressure level can be expressed as:

$$L_{eq,T} = 10\log\left(10^{L_{eq,T,source}/10} + 10^{L_{eq,T,non-relevant}/10} + 10^{L_{eq,T,unknown}/10}\right)\ \text{dB}, \qquad (1)$$

where $L_{eq,T,source}$ represents the measured contributions which can be attributed to the sound source of interest with a high degree of plausibility, $L_{eq,T,non-relevant}$ gathers components which can be associated to non-relevant sound sources with a high degree of plausibility, and $L_{eq,T,unknown}$ collects contributions which cannot not be classified as relevant nor non-relevant with a satisfactory degree of plausibility. To our knowledge, the existence of $L_{eq,T,unknown}$ cannot be avoided with current technology, as it arises from the limitations of available methods further discussed in later sections.

Unwanted events are a category of non-relevant sounds typically represented by discrete sound event data of short duration, such as aircraft or ground traffic passings. Defining

$$L_{eq,T,non-relevant} = 10\log\left(10^{L_{eq,T,residual}/10} + 10^{L_{eq,T,unwanted}/10}\right)\ \text{dB}, \qquad (2)$$

with $L_{eq,T,unwanted}$ as the term representing unwanted events and $L_{eq,T,residual}$ representing remaining sounds after both unwanted events and relevant sounds are suppressed, Equation (1) can be expressed as:

$$L_{eq,T} = 10\log\left(10^{L_{eq,T,source}/10} + 10^{L_{eq,T,residual}/10} + 10^{L_{eq,T,unwanted}/10} + 10^{L_{eq,T,unknown}/10}\right) \text{ dB}. \tag{3}$$

The metric $PL_{eq,T}$ was proposed so that

$$PL_{eq,T} \approx L_{eq,T,source}. \tag{4}$$

In other words, $PL_{eq,T}$ was developed to obtain better estimates of the equivalent sound pressure level of the relevant sound source.

Unwanted events can be discarded from the data as described in ISO 1996-2. However, and assuming that relevant and residual sound sources are active simultaneously, simply discarding the terms $L_{eq,T,residual}$ and $L_{eq,T,unknown}$ would result in equivalent sound pressure levels that might not be representative of the actual operational conditions of the sound source of interest, as discussed in [2]. The $PL_{eq,T}$ model addresses these issues and can be expressed as:

$$PL_{eq,T} = 10\log\left(10^{L_{eq,T,source}/10} + 10^{L_{eq,T,DummySource}/10} + 10^{(L_{eq,T,unknown}-2\text{ dB})/10}\right) \text{ dB} \tag{5}$$

where $L_{eq,T,source}$ is kept as measured, the $L_{eq,T,residual}$ component is replaced by $L_{eq,T,DummySource}$ to compensate for assumed operational conditions of the source of interest while residual sounds were dominant, $L_{eq,T,unknown}$ is corrected by 2 dB and $L_{eq,T,unwanted}$ is discarded. The rationale behind each of the proposed terms in $PL_{eq,T}$ is described in sections 2.2 to 2.5.

$PL_{eq,T}$ can also be expressed as follows:

$$PL_{eq,T} = 10\log\left(10^{L_{eq,T,}/10} - 10^{L_{eq,T,residual}/10} + 10^{L_{eq,T,DummySource}/10} - 10^{(L_{eq,T,unknown})/10} + 10^{(L_{eq,T,unknown}-2\text{ dB})/10} - 10^{L_{eq,T,unwanted}/10}\right) \text{ dB}, \tag{6}$$

where Equations (5) and (6) are equivalent and reach the same result.

### *2.1.1. Change in notation from previous work*

Note that our previous work used a different notation. For clarification, the term $L'_{eq,T,irrelevant}$ that we established in [2] and [4]:

$$L'_{eq,T,irrelevant} = L_{eq,T,DummySource}. \tag{7}$$

The change in notation has been introduced to add clarity to the concept of $PL_{eq,T}$.

Note also that the $L_{eq,T}$ models presented in [2] and [4] did not account for unwanted events. Therefore, Equation (2) has been introduced and $L_{eq,T,irrelevant}$ in those previously presented models has been renamed to $L_{eq,T,residual}$ in Equation (3).

## 2.2. Relevant sounds, $\boldsymbol{L_{eq,T,source}}$

For the purposes of this paper, relevant sounds are identified by their location in 3D space by using Noise Compass [2], with calculations being performed on the cloud platform NorCloud [7].

Noise Compass consists of a device featuring 8 MEMS microphones disposed circularly at two different heights. Using cross-correlation techniques, a matrix of 14 vectors and time lags is established for different combinations of microphones. An estimate of the direction of arrival of the dominant sound is then obtained with NorCloud by the method of least mean squares. The estimated direction of arrival is decomposed into azimuth and elevation components. These components are found for each data sample measured with a class 1 sound level meter. Additionally, a quality indicator ranging from 0 to 1 is computed to provide information about the reliability of the estimated direction of arrival. See [2] for details regarding the quality indicator.

Since the location of the relevant sound source is known and stationary (a factory, a road, a construction site, etc.), the relevant sounds can be easily determined by comparing the azimuth and elevation computed for each data sample, with the known azimuth and elevation of the sound source of interest. The underlying assumption is that the locations of relevant and residual sources do not overlap in 3D space. The quality indicator must be evaluated for all samples to avoid false positives and false negatives. For the purposes of this study, only samples with a quality indicator ≥ 0.7 have been considered when classifying them as relevant.

Classifying a sample as relevant implies that, with high plausibility, the relevant sound source was dominant at that time. Residual sound sources might have been active simultaneously, but the level difference was ≥ 3 dB.

## 2.3. Managing residual sounds: $\boldsymbol{L_{eq,T,residual}}$ and $\boldsymbol{L_{eq,T,DummySource}}$

The component $L_{eq,T,residual}$ in Equation (3) is identified by the associated locations in 3D space with the same method described in 2.2. If the computed azimuth and elevation correspond to locations outside the defined space of the relevant sound source, and the quality indicator is ≥ 0.7, the sample is considered as residual sound with a high level of plausibility.

Classifying the sample as residual sound implies that at least one residual sound source was dominant at the time. The sound source under study might have been active simultaneously, but the level difference between sources was ≥ 3 dB.

Since the contribution of residual sound sources is measured, $L_{eq,T,residual}$ can be discarded. However, under the assumption that the relevant sound source is active continuously, discarding $L_{eq,T,residual}$ represents the extreme case where the contributions of the relevant sound source at the time did not affect the measured results of equivalent sound pressure level. This condition cannot be necessarily confirmed with the data available from Noise Compass, but it can be assumed that the contributions of the relevant sound source were at least 3 dB lower than $L_{eq,T,residual}$, while the residual sound sources were dominant.

$L_{eq,T,DummySource}$ is therefore introduced in Equations (5) and (6). This component represents the sound pressure level of the relevant sound source, while residual sound sources are dominant. Our previous studies reported in [2] and [4] compared several methods to estimate plausible levels for this component (called $L'_{eq,T,irrelevant}$ in previous papers, see 2.1.1). In the study reported here, only one of the methods analyzed is implemented:

$$L_{eq,T,DummySource} = \frac{1}{N}\sum_{i=1}^{N} L_{eq,T,unknown_i} \tag{8}$$

where $L_{eq,T,DummySource}$ is the arithmetic average of repeated measurements of $L_{eq,T,unknown}$ over $N$ days.

It can be argued that averaging repeated measurements of $L_{eq,T,source}$ would be a better value for $L_{eq,T,DummySource}$, since $L_{eq,T,source}$ can be directly tracked to the source of interest with high plausibility. Our experience shows, however, that the resulting $PL_{eq,T}$ would be overestimated in most cases, yielding values that are higher than the measured $L_{eq,T}$.

## 2.4. Managing unknown components: $L_{eq,T,unknown}$ – 2 dB

When analyzing the data obtained with Noise Compass, a low quality indicator implies that the system was not able to compute the direction of arrival for the dominant source with sufficient reliability. Typically, this occurs when the sound pressure level of simultaneous sound sources is similar, i.e. there is no dominant sound source. Low quality indicators are also common when there is no identifiable sound source and measured environmental noise can be considered low (typically $\leq$ 55 dB). In this study, all samples with a quality indicator < 0.7 are included in the $L_{eq,T,unknown}$ component of Equation (3).

The presence of sounds that cannot be automatically classified as relevant or residual is a methodological limitation that affects other implementations in the market. Increasing the number of sensors can contribute to disambiguating the affected samples, but this approach has not been tested in the present study and remains as further work.

Considering the presence of at least two simultaneously active sound sources where one of them is the relevant sound source, previous work [4] has suggested that the $L_{eq,T,unknown}$ component can be corrected to compensate for the contribution of the residual sources. Since a low quality indicator can be associated with two or more sources with similar levels at the measurement point, the limiting case is that of two sound sources with equal sound pressure level. In the limiting case, then, it can be assumed that each sound source has a level equal to $L_{eq,T,unknown} - 3$ dB, assuming equal frequency content of the sources.

Since we have set a threshold of 0.7 for the quality indicator in this study, some difference between the sound pressure levels from the individual sources adding to $L_{eq,T,unknown}$ can be expected. For two sound sources with a level difference of 2.3 dB, it can be shown that the sound pressure level of the noisiest sound source is equal to $L_{eq,T,unknown} - 2$ dB. This is an acceptable trade-off for our study, since bigger level differences would yield higher quality indicators – allowing the categorization of sound samples as relevant or residual, but not unknown.

In Equations (5), then, $L_{eq,T,unknown}$ is corrected by subtracting 2 dB.

### 2.5. Managing unwanted events: $L_{eq,T,unwanted}$

Well established methods to identify unwanted events are sound pressure level threshold exceedance and discrimination tests performed by human operators, which can be time-consuming tasks. Recent literature has shown that AI can be efficiently implemented to automate the identification of unwanted events [6].

In the context of sound monitoring, AI can be used to train a model so that it can classify different types of noise events based on features extracted from the sound data. Classification of noise events is then automatically conducted by the model, analyzing information such as frequency content, duration and amplitude of the signal.

The AI model used in our study was trained on a dataset of labeled noise events, allowing it to learn and identify sounds of interest. The training required the development of a classification taxonomy tailored to the project. The model was then evaluated by performance metrics such as accuracy, precision, recall and F1-score. Details of the model and its evaluation can be found in [6].

The AI model used is implemented in the tool NoiseTag. Events identified as unwanted are removed from the measurements, as Equations (5) and (6) indicate.

Since the identification of unwanted events is performed based on features extracted from the sound data, AI is a robust method to identify events regardless of their location in 3D space.

### 2.6. Comparison with ISO 1996-2

In this study, $PL_{eq,T}$ results are compared with results obtained by applying the procedures described in ISO 1996-2.

ISO 1996-2 states that all data including unwanted events or with too high residual sound must be removed before evaluating the measurement results. According to the standard, the level gap between average residual sound and the onset of a measurement shall be at least 3 dB and preferably more than 5 dB. If the sound pressure level of residual sound is ≤ 3 dB below the measured sound pressure level, no corrections are allowed. The measurement uncertainty is, in such a case, large and the requirements of the test methods are not fulfilled. If the sound pressure level of the residual sound is > 3 dB below the measured sound pressure level, the level is corrected according to:

$$L = 10\log\left(10^{L'/10} - 10^{L_{res}/10}\right)\text{ dB}, \tag{9}$$

where $L$ is the estimated sound pressure level of the sound source of interest, $L'$ is the measured sound pressure level and $L_{res}$ is the residual sound pressure level.

Substituting the components from Equation (3) in Equation (9):

$$10\log\left(10^{L_{eq,T,source}/10} + 10^{L_{eq,T,unknown}/10}\right) = 10\log\left(10^{L_{eq,T}/10} - 10^{L_{eq,T,residual}/10} - 10^{L_{eq,T,unwanted}/10}\right)\ \mathrm{dB}, \quad (10)$$

which means that $PL_{eq,T}$ results from Equation (5) will be compared with $10\log\left(10^{L_{eq,T,source}/10} + 10^{L_{eq,T,unknown}/10}\right)$ from Equation (10).

## 3. CASE STUDY

Noise from a construction site in Drammen, Norway, was analyzed with the methodology presented in the previous sections. An unattended noise monitoring station consisting of a class 1 sound level meter Norsonic Nor145 and a Noise Compass device was mounted in the site and connected to the platform NorCloud.

The construction site was located in a complex setting with neighboring industries, railway, motorway and residential areas. Four different sectors were defined with Noise Compass to delimit the areas of relevant and residual sources. Three of these sectors are shown in Figure 1. The fourth sector, corresponding to the area above the construction site, is not shown.

Figure 1: Location of the sound monitoring station, with three of the four sectors defined. Red: road and railway (residual sound), Blue: Industry (residual sound), Green: construction site (relevant sound).

Data from 2022-08-29 to 2022-09-11 was analyzed. From these, only weekdays (Monday to Friday) will be presented as there was no activity in the construction site during weekends. Table 1 presents the calculated values for each defined sector, identified as described in section 2. All values are calculated from 07:00 to 19:00.

The unwanted events shown in Table 1 correspond to train passings with durations ranging from 6 seconds to 12 seconds. These contributions have a high sound pressure level, but the equivalent value calculated over 12 hours is low due to the short duration of the events.

Table 1: Calculated values for ten weekdays, for each defined sector.

| **Date** | $L_{eq,12h,source}$ dB(A) | $L_{eq,12h,residual}$ dB(A) | $L_{eq,12h,unknown}$ dB(A) | $L_{eq,12h,unwanted}$ dB(A) | $L_{eq,12h}$ dB(A) |
|---|---|---|---|---|---|
| 2022-08-29 | 68.1 | 63.9 | 65.2 | - | 70.8 |
| 2022-08-30 | 69.4 | 67.1 | 64.2 | 47.4 | 72.2 |
| 2022-08-31 | 69.4 | 66.6 | 63.7 | - | 71.9 |
| 2022-09-01 | 62.0 | 60.1 | 58.6 | - | 65.2 |
| 2022-09-02 | 57.1 | 54.9 | 58.4 | - | 61.8 |
| 2022-09-05 | 66.2 | 62.3 | 61.4 | - | 68.6 |
| 2022-09-06 | 66.7 | 59.1 | 61.1 | 46.0 | 68.4 |
| 2022-09-07 | 64.9 | 61.3 | 62.0 | 50.4 | 67.9 |
| 2022-09-08 | 63.6 | 61.1 | 60.1 | - | 66.6 |
| 2022-09-09 | 59.9 | 62.0 | 58.8 | - | 65.2 |

The value of $L_{eq,T,DummySource}$ computed with Equation (8) was 61.3 dB. This value was used for the computations of all $PL_{eq,T}$ results.

Table 2 presents the measured levels, the calculated levels with the methods from ISO 1996-2 given by Equation (10) and the results of the proposed $PL_{eq,T}$ model given by Equation (5).

Table 2: Comparison of measured and calculated levels with the proposed partial equivalent sound pressure level model and the ISO 1996-2 methods.

| **Date** | $L_{eq,12h}$ **(Eq. 3, original measurement)** dB(A) | $L_{eq,12h}$ **(Eq. 10, ISO 1996-2)** dB(A) | $PL_{eq,12h}$ **(Eq. 5, proposed model)** dB(A) |
|---|---|---|---|
| 2022-08-29 | 70.8 | 69.9 | 69.9 |
| 2022-08-30 | 72.2 | 70.6 | 70.7 |
| 2022-08-31 | 71.9 | 70.4 | 70.6 |
| 2022-09-01 | 65.2 | 63.6 | 65.3 |
| 2022-09-02 | 61.8 | 60.8 | 63.6 |
| 2022-09-05 | 68.6 | 67.5 | 68.1 |
| 2022-09-06 | 68.4 | 67.8 | 68.4 |
| 2022-09-07 | 67.9 | 66.7 | 67.4 |
| 2022-09-08 | 66.6 | 65.2 | 66.3 |
| 2022-09-09 | 65.2 | 62.4 | 64.5 |

The results from Table 2 are also presented graphically in Figure 2.

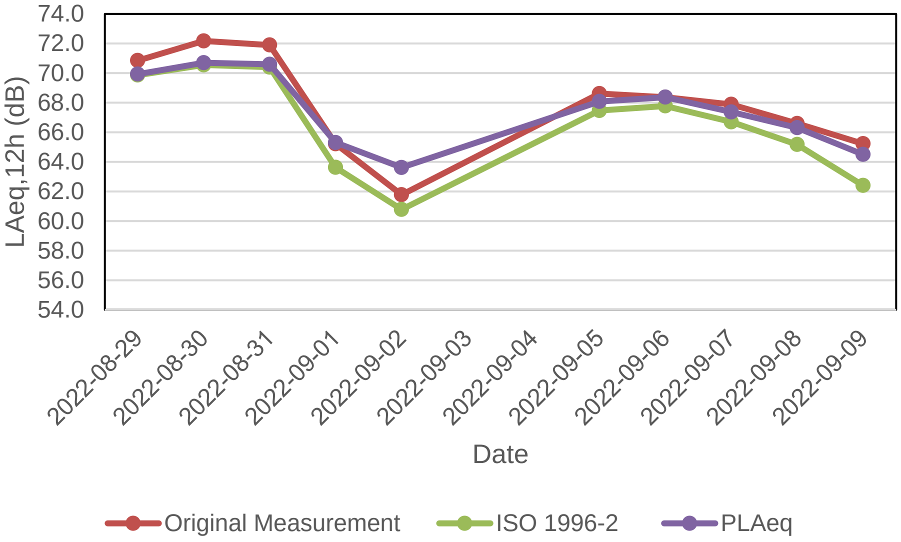

Figure 2: Comparison of measured and calculated levels with the proposed model of partial equivalent sound pressure level and the ISO 1996-2 methods.

## 4. DISCUSSION

Results for 2022-08-29 to 2022-08-31 suggest that the proposed $PL_{eq,T}$ model yields values similar to those obtained with the well-established ISO 1996-2 methods.

The $PL_{eq,T}$ results for 2022-09-01 and 2022-09-02 are higher than the original measurements. This can be explained by observing the values used for $L_{eq,T,DummySource}$, relative to the values of the other components. As explained in 2.3, $L_{eq,T,DummySource}$ is used as a replacement for $L_{eq,T,residual}$ to account for typical sound pressure levels of the relevant sound source when it is not dominant. Since $L_{eq,T,DummySource} > L_{eq,T,residual}$ while the other components have a relatively low value, $L_{eq,T,DummySource}$ dominates and the resulting $PL_{eq,T}$ is higher than the actual measurement. Instances like these must be avoided and rules can be implemented in data processing tools (e.g. NorCloud) to automatically reject the use of $L_{eq,T,DummySource}$ and keep the measured $L_{eq,T,residual}$ value in such cases.

Results for the remaining dates are closer to the measured values than to those computed with ISO 1996-2 methods. The data suggests that this occurs when $L_{eq,T,source}$ has a significantly higher level than $L_{eq,T,residual}$. For the date where $L_{eq,T,residual}$ takes a higher value compared to the other components (2022-09-09) the $PL_{eq,T}$ model yields results that are in between the original measurements and those calculated with ISO 1996-2 methods.

## 5. CONCLUSIONS

The $PL_{eq,T}$ model was extended to account for unwanted events and compensate for uncategorized or unknown sounds, under the assumption that two sound sources were active simultaneously. Sounds were categorized as relevant, residual, unknown and unwanted by using direction-of-arrival techniques and AI, implemented in the Norsonic tools Noise Compass, NoiseTag and NorCloud. Results show that the values obtained with the $PL_{eq,T}$ model are in line with those calculated with ISO 1996-2, suggesting the validity of the model. Limitations are encountered when $L_{eq,T,DummySource}$ is higher than the value it replaces, but this can be avoided by implementing simple rules in the data processing software. Even though proprietary tools were used in the study, $PL_{eq,T}$ is a generalized model and can be utilized with other devices, software and platforms available in the market.

## ACKNOWLEDGEMENTS

We gratefully acknowledge Vestre Viken HF in Norway for allowing us to place a noise monitoring station in the construction site of the new hospital in Drammen.

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