Impact of Individual Anomalous Noise Events on the Monitoring of Traffic Noise in Urban Areas

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Summary
At least one million healthy life years are lost every year from traffic-related noise in the western part of Europe according to the World Health Organization. Other diseases have been linked with environmental noise, such as sleep disturbance, heart illnesses or tinnitus. The Environmental Noise Directive 2002/49/EC (END) and the CNOSSOS-EU framework are the main instruments provided by the European Union (EU) to identify and combat the noise pollution in the European countries. The END asks the EU member states to publish noise maps and the consequent action plans every five years. In order to automatize the process of noise monitoring, several projects are aimed at implementing a noise-mapping system by means of a wireless acoustic sensor network. However, to analyze the impact of traffic noise on public health, noise events non-related to traffic should be removed from the noise map computation since they may bias significantly the result. This work evaluates the impact of individual anomalous noise events on the equivalent sound level computation in relation to their Signal-to-Noise Ratio (SNR) and duration. The analysis is conducted within the framework of the LIFE DYNAMAP project, which is aimed at representing the acoustic impact of road infrastructures through dynamic noise mapping. The experiments consider four hours of real-life acoustic data recorded in the urban area of Milan (Italy), defining as critical those anomalous noise events exceeding the A-weighted equivalent sound level computation by more than 2 dB in a 5-min integration time. The results evidence, on the one hand, the presence of critical anomalous noise events, and on the other hand, prove that both SNR and duration are relevant parameters to characterize these events, which should be removed to avoid biasing subsequent health studies or action plans.

PACS no. 43.50.Lj, 43.50.Rq, 43.50.Yw, 43.60.Bf

1. Introduction

Noise pollution has been proven to cause several severe illnesses among other disturbances and stress, as diabetes [1], mental-related [2] and permanent hearing loss [3]. Specifically, it has been stated by the World Health Organization (WHO) that a loss of a million healthy life years is caused by noise pollution in western Europe every year [4]. This number is increasing every year due to the expansion of transportation systems [5], basically in the most dense urban areas. Furthermore, research connect noise exposition to other social and economic aspects [5], which should be also taken into account. Besides, researchers connect tiredness and sleep disturbances specifically with road-traffic noise [6] and Jakovljevic concludes that it is the most significant source of noise in urban areas according to the residents [7]. Besides, a set of human-related indicators have been defined in [8] in order to consider the quality of life in a neighborhood.

For this reason, directives and projects assessing noise monitoring focus in urban agglomerations and, particularly, in road infrastructures. Both the Environmental Noise Directive 2002/49/EC (END) [9] and the CNOSSOS-EU framework [10], were created by the European Union to combat the increasing noise pollution in the European countries. The END aims at determining the noise exposure, making the updated information related to noise available to citizens besides preventing and reducing the environmental noise where necessary. It requires the European countries to publish noise maps and the related action plans every five years for agglomerations with more than 100,000 inhabitants and other major roads, railways and airports.

Several projects have been developed worldwide to monitor noise pollution by means of Wireless Acoustic Sensor Networks (WASNs), as the UrbanSense project

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pretends to monitor urban noise and other pollutants in real-time in Canada [11]. In the UK, the DREAM-Sys project uses a distributed sensor network to monitor noise [12]. Also in India, a project is conducted to register the acoustic equivalent level and analyze the collected data statistically [13]. Other cities are making steps to become smart cities, as Pisa, with the SENSEable Pisa Project monitoring sound levels in real time [14], Monza, through a LIFE project focused on low-cost monitoring systems [15] and Barcelona, putting emphasis on resource efficiency and on urban infrastructure impact [16].

However, in order to avoid biasing the study of the impact of Road-Traffic Noise (RTN) on health when using an automatic monitoring system, several events non-related to traffic should be detected and removed from the equivalent noise level computation, i.e., Anomalous Noise Events (ANEs). To this end, the LIFE DYNAMAP project has designed and deployed a low-cost WASN to monitor the equivalent sound levels at the same time that removes the detected ANEs from the noise map computation [17]. According to the project specifications, each WASN sensor outputs and A-weighted [18] equivalent sound level of the road-traffic noise every five minutes, referred as L_{A300s} hereafter. In previous research, the authors presented a methodology of analyzing the ANE impact by means of other two metrics, SNR and duration [19].

In this paper, the impact analysis methodology is summarized and evaluated for a representative selection of the events, with a deeper analysis on the resulting impact depending on the SNR and the duration of each event. In this work we study the relevance of SNR and duration when evaluating the impact, as diverse ANEs could have an impact to the equivalent sound level. The authors will analyze if long low-SNR ANEs can bias the L_{Aeq} as well as high-SNR short ANEs. Finally, the authors prove the existence of ANEs that bias the L_{A300s} computation by more than 2 dB in a 5-min integration time, these are considered critical ANEs. For this purpose, a dataset recorded in an urban environment in Milan is used [20], developed in the framework of the DYNAMAP project [17].

This paper is structured as follows. Section 2 describes the methods of event characterization used in this work, including SNR, duration and impact on the L_{Aeq}. In Section 3, high- and low-level analysis are conducted by measuring the impact in relation to SNR and duration. Finally, discussion is presented in Section 4 and conclusions in Section 5.

2. Evaluation of the ANE impact on the L_{Aeq} computation

In order to analyze the impact of individual ANE to the L_{Aeq}, two other metrics are considered [19]: the event duration and the SNR with respect to the surrounding RTN. The three calculations combined -duration, SNR and impact-, lead to understand the effect of the ANEs to the noise map, as they represent time domain, saliency quantification and the total affectation to the L_{Aeq}, respectively. In this section the evaluation procedure is detailed for each of the three metrics.

2.1. Duration

The duration is defined as the difference between the first and the last time stamps of the analyzed event in seconds obtained after the manual labelling process. As stated in previous works, the nature of the ANE and acoustics of the recording site may both affect the duration [20]. The duration has direct relevance on the impact, as the latter is measured in a delimited segment of 5 min, as defined in the DYNAMAP project specifications. Thus, it is relevant to measure the duration and figure out the temporal importance of the ANE within the time interval where it is present.

2.2. SNR

The energy of the event is also a relevant parameter to model an ANE so as to evaluate the impact of its presence in the L_{Aeq} computation for a given integration time. In order to compute the energy of an ANE in relation to the background RTN, a measure based on the Signal-to-Noise Ratio (SNR) is used. The SNR is defined as the ratio of the signal power to the noise power [21], where the signal belongs to the acoustic power of the ANE and the noise refers to the background RTN. The acoustic power of an acoustic event is calculated as expressed by equation 1, where the sound event is $x(t)$ and N is the number of samples of the event given a sampling frequency.

$$P_x = \sum_{t=1}^{N} \left(\frac{x(t)^2}{N} \right) \quad (1)$$

To obtain the acoustic power of the ANE, it should be isolated from the RTN lying in the background of the same time interval. In several fields, where one may assume that the noise is stationary, it could be measured in a time interval where no anomalous events are present. Therefore, in this work, the signal evaluated in the SNR calculation will consist of the power of both ANE and RTN, and the noise power will be evaluated in the immediate adjacent time intervals [19]. Thus, the SNR is calculated as expressed by equation 2, where P_{ANE} is the acoustic power of the recorded signal in the time interval of the ANE and P_{RTN} is the acoustic power of the surrounding road-traffic noise.

$$SNR = 10 \, log_{10} \left(\frac{P_{ANE}}{P_{RTN}} \right) \quad (2)$$

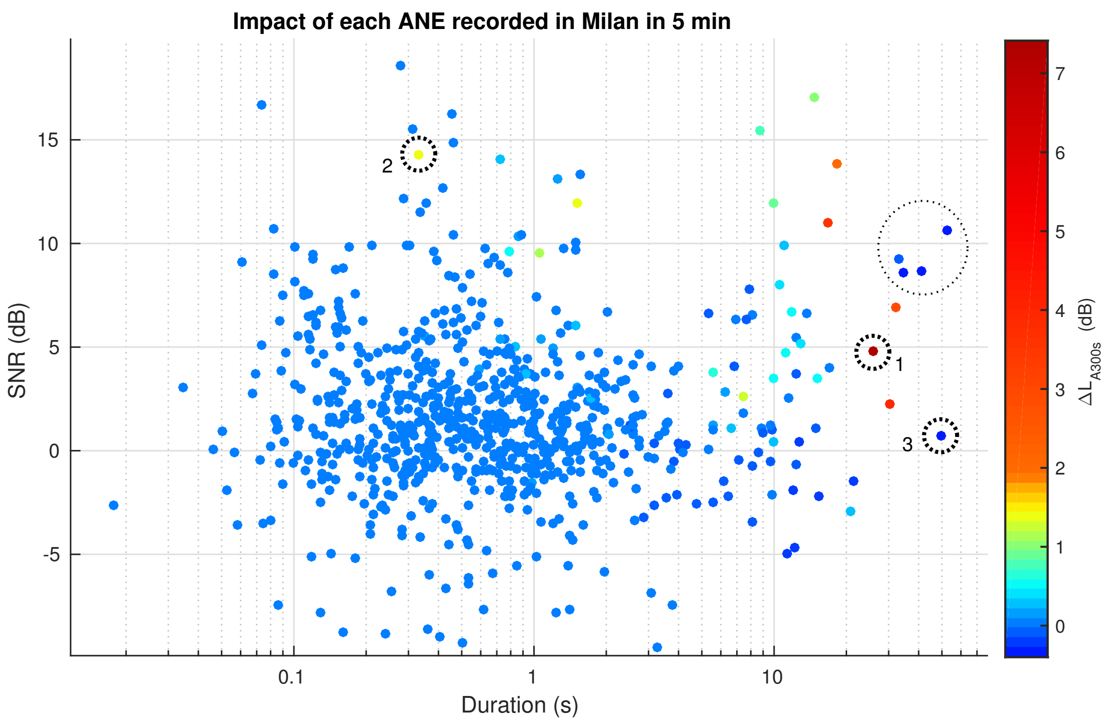

Figure 1. Scatter plot of all the individual ANE impacts to the L_{A300s} in relation to duration and SNR in Milan.

It is worth mentioning that the acoustic power of the RTN is evaluated using both prior, RTN_1, and posterior, RTN_2, recorded fragments in equal parts.

Both duration and SNR are separate measures in distinct magnitudes and could be both useful to model and understand the impact indicator as they assess complementary domains.

2.3. Impact Evaluation

The impact calculation is based on the equivalent sound level measure after the A weighting is applied for a given interval of time [18], i.e. L_{Aeq}. The A-weighted equivalent noise level (L_{Aeq}) is evaluated using the free Matlab *Continuous Sound and Vibration Analysis* toolbox developed by Edward L. Zechman[1] considering a 1-s evaluation time.

The impact of an individual ANE is obtained by comparing the L_{Aeq} computed within the analyzed time interval in two cases: the first, considering the whole acoustic data, and the second, after removing the ANE. After that, the effects of the ANE can be quantified in the time period of interest. In order to remove a certain ANE from the L_{Aeq} calculation, the time interval belonging to the ANE is replaced with a linear interpolation from the last RTN time stamp before the event and the following one after the event. To interpolate, the L_{A1s} is used as acoustic samples cannot be interpolated without changing the sound and altering the L_{Aeq} value [19]. Finally, the impact of each individual ANE on the L_{Aeq} value is represented as ΔL_{Aeq}.

In this case, the time interval is chosen after the DYNAMAP project specifications, that pretends to output a sound level measure every five minutes applying the A weighting. Thus, the impact is shown as ΔL_{A300s} and the unit is dB, because it is the difference between the two L_{Aeq} calculations (with and without the concerning ANE).

According to the *Assessment of exposure to noise* of the European Commission, the maximum tolerated change is 2 dB for a measure of a given segment [22]. For this reason, the 2-dB threshold is considered in this work to discern critical ANEs in the L_{A300s} measurement.

3. Experiments

In this section, the individual impact analysis of the ANEs is presented for the urban pilot area of the DYNAMAP project using real-life acoustic data recorded in the city of Milan. First, the used dataset is introduced with the recording and site information. After that, a high-level analysis is conducted, including all

[1] https://es.mathworks.com/matlabcentral/fileexchange/21384-continuous-sound-and-vibration-analysis

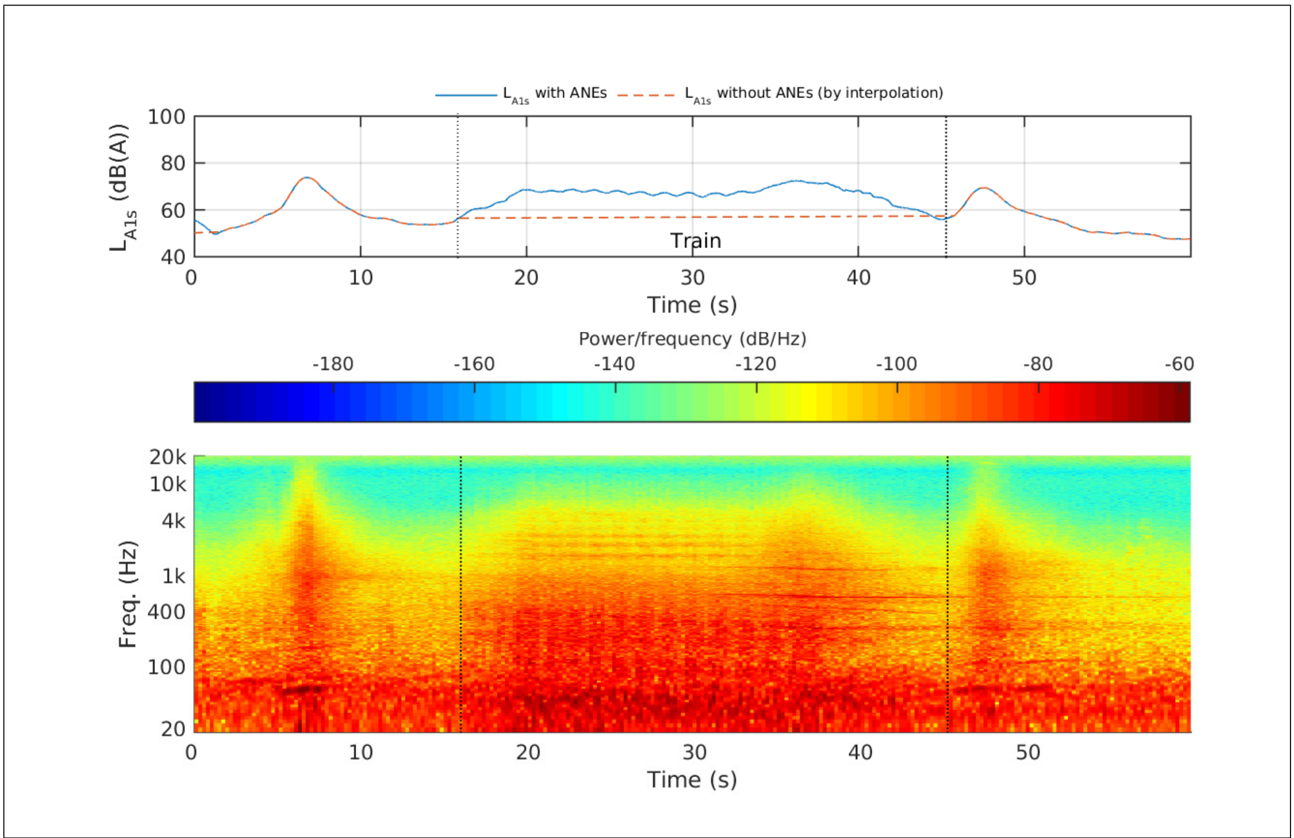

Figure 2. Example of a critical train recorded in Site 4 which presents a long duration and a notable SNR. Belongs to the marked as *1* in Figure 1.

individual impacts, duration and SNR measurements, and highlighting the most representative ANEs. Finally, a low-level analysis is carried with the chosen ANEs, which pretends to present an illustrative comparison involving both SNR and duration metrics and the impact evaluation.

3.1. Milan Urban Dataset

The acoustic dataset has been collected within District 9 of the city of Milan [20]. It contains 4 h and 24 min of acoustic data collected from 12 different representative recording sites of this urban area (from now on, named Site 1 to Site 12, for more information, the reader is referred to [20]). After being carefully labelled by several experts, 711 ANEs have been identified, representing the 12% of the total recorded data. The anomalous events include both short impulse-like ANE (e.g., dogs barking) and long events with relevant SNR (e.g., trains or trams), together with events with high and low acoustic saliency with respect to the background road traffic noise. More details about the dataset can be found in [20].

3.2. High-Level Analysis

The DYNAMAP's WASN is designed to output an L_{Aeq} value each 5 min, thus, the equivalent sound level integrates the audio of a whole 5-min interval. For this reason, in this work, the individual analysis of the impact is computed using the L_{A300s}.

In Figure 1, the individual 5-min impact analysis presented in [19], is depicted differently in order to facilitate the analysis of the impact versus duration and SNR metrics. In the x-axis, the duration of the ANEs is represented in the logarithmic scale for illustrative purposes, leaving the SNR metric depicted in the y-axis. The impact of each ANE is represented according to a color scale, where the colors shift gradually from the minimum to the 2-dB threshold and the shading is softer from the threshold to the maximum; as mentioned above, this threshold is used to discern critical ANEs.

The reader may observe, at least, four critical events, representing a 0.6% from the total of ANEs. These events are (ordered from lower impact to higher impact) a 2.8-dB train, a 3.5-dB truck towing system, a 3.9-dB siren and another train of 7.4-dB impact. They range from 17 to 32 s of duration and from 2.2 to 11.0 dB of SNR. Eleven other events have an impact between 0.5 and 2 dB, of which one is near the threshold of 2 dB, with 1.9 dB, a 18-s train of 13.8 dB of SNR.

With a detailed observation of Figure 1, one can conclude that all critical ANEs present a duration of more than 17 s, however, four ANEs marked a the thin-dotted circle present a high duration and SNR

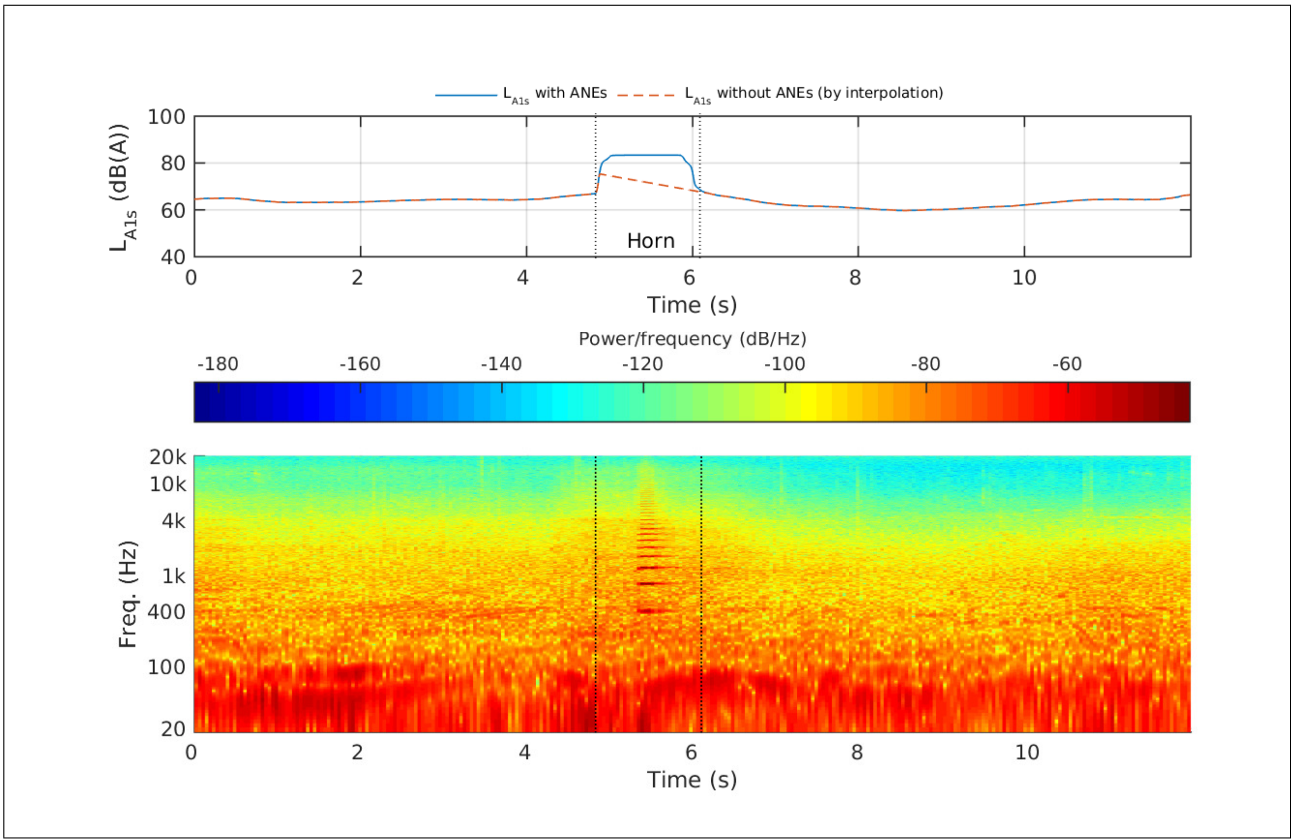

Figure 3. Example of a medium-impact horn recorded in Site 12 which presents a short duration and a high SNR. Belongs to the marked as *2* in Figure 1.

and have a very low impact. These ANEs have the same typology, a music sound coming from speakers. Other ANEs present an impact between 1 and 2 dB with a duration ranging from 0.3 to 1.5 s but with a high SNR starting at 9 dB.

The ANEs presenting a negative SNR have always a low impact and tend to be of short duration. In these cases, the energy of the event is below the RTN levels and usually occurs with low intensity ANEs that can only be appreciated when the RTN is low, implying that the ANE has a lower level than the surrounding background noise.

3.3. Low-Level Analysis

In this section, a low-level analysis of the individual impacts is conducted based on the marked events in Figure 1: *1)* the ANE presenting the highest impact (a train sound), *2)* a horn sound showing medium impact with a high SNR and a low duration, and *3)* a long music sound with a low SNR presenting a low impact.

All analyzed examples are illustrated with the equivalent sound levels above and the associated spectrogram of the audio below. The L_{A1s} is plotted in two curves, the blue line represents the sound level of the raw audio and the dashed red line depicts another L_{A1s} where the ANEs have been replace by the linear interpolation. All figures are plotted in the same y-axis scale to improve the comparison between them.

1. The highest impact of an individual ANE is a train recorded in Site 4, which presents an impact on the L_{A300s} of 7.4 dB, with a duration of 26 s and an SNR of 4.8 dB. In Figure 2, the reader may appreciate that the L_{A1s} curve of the raw audio is sustained more than 10 dB(A) above the interpolated curve. In the spectrum, several concentrated mid and high frequencies are present during the whole event duration and the low frequencies show a sustained increased power in comparison with the previous and subsequent RTN.

2. Another ANE worth to mention is depicted in Figure 3, a salient horn recorded in Site 12 that presents an impact of 1.4 dB. It has an SNR of 14.3 dB and a duration 0.4 s (although the interpolation windowing of 1 s alters the graph). In the spectrum, a clear shape indicates the horn.

3. The last example is a long music sound with a negative impact of -0.3 dB. As appreciated in Figure 4, it has a duration of 50 s and presents an SNR of 0.7 dB. In the spectrum, several lines can be appreciated indicating that the music volume is not constant.

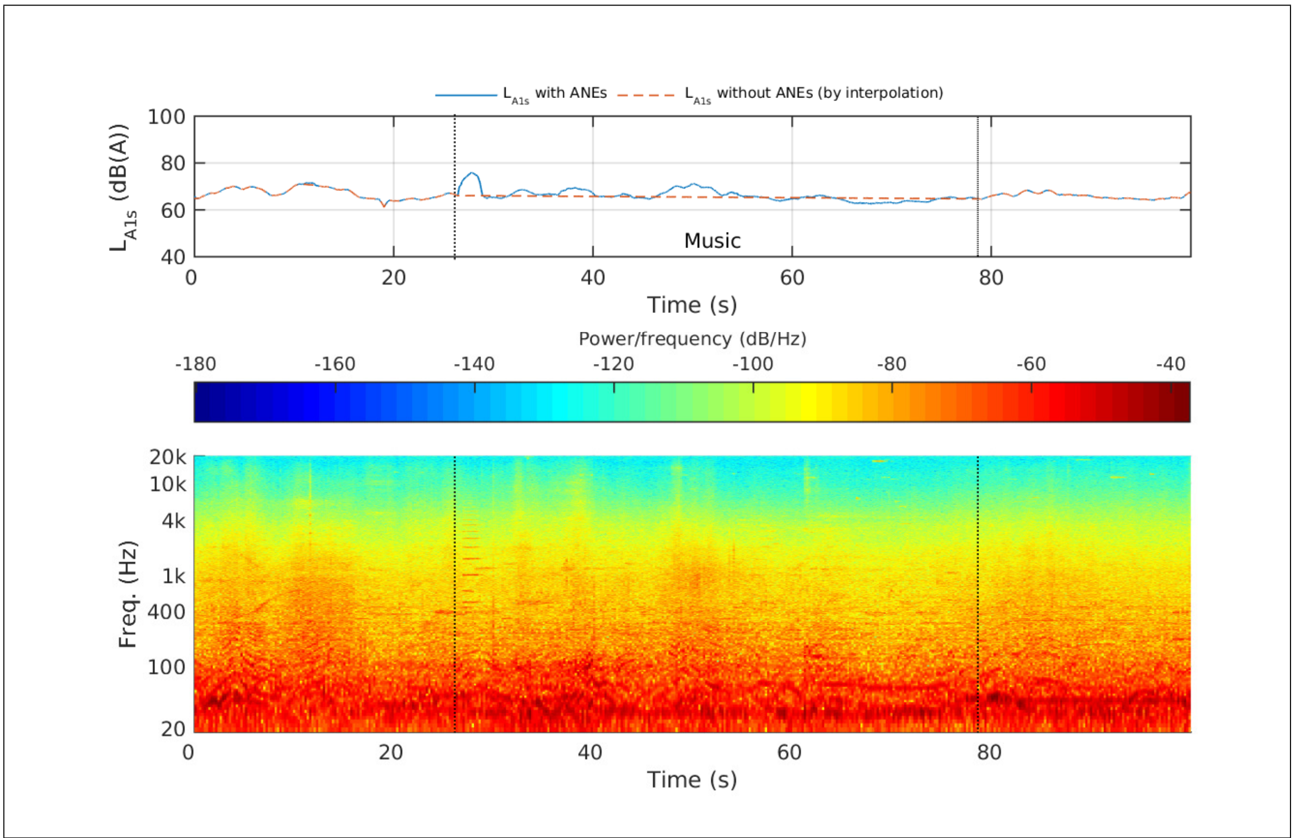

Figure 4. Example of a low-impact music sound recorded in Site 3 which presents a long duration and a low SNR. Belongs to the marked as *3* in Figure 1.

4. Discussion

In this work, a high- and low-level analysis of the impact is conducted using the metrics in [19]. In the analysis of all the dataset, three distinctive patterns of impact events have been appreciated: *i)*, ANEs with long duration and significant SNR present impact when evaluated, *ii)* short events with high SNR may also have a significant impact in the 5-min time evaluation and *iii)* ANEs with both significant duration and SNR may have also a significant impact in the equivalent level.

A representative sample of the individual analysis has been analyzed in detail, as an example to describe the mentioned patterns. In the first example, depicted in Figure 2, a long ANE with significant SNR has proven to have a high impact, in fact, the highest of the dataset. After that, the second example, a horn illustrated in Figure 3, allows the reader to understand the importance of the SNR by presenting a notable impact and being extremely short in duration. Finally, Figure 4, depicts an example of long ANE that has not significant impact on the L_{A300s}, giving value to the SNR measurement again.

Concerning the SNR measure, many ANEs present negative SNR, due to the method of evaluation of the metric; the background noise is not stationary and can affect the evaluation of the metrics of each event. Besides, it is also worth to emphasize on a case where a long duration and a high SNR are not enough to produce a high impact to the L_{A300s}. As mentioned above, these four ANEs, marked in Figure 1 with a thin-dotted circle, are labelled as music coming from speakers. They are long anomalous events, and due to the method to evaluate the metric, the longer the analyzed event, the more samples of RTN have to be used to evaluate the SNR. As the duration of these events is very high, from 33 to 53 s, the RTN data samples used in the SNR calculation are separated 15 to 26 s before and after the ANE, depending on the case. This means that RTN far away from the ANE can have multiple variations, and even other events, and can alter the result of the SNR calculation as it takes into account not only surrounding RTN. Thus, one of the elements to take into account in future work is that more variables maybe needed into consideration to analyze all kinds of events or the SNR metric should be refocused.

5. Conclusions

This works shows the role of duration, SNR and impact in the description of the ANE that can be found in the automatic monitoring of road-traffic noise. The duration, as it is concluded to be a key metric (as seen in Figure 2), but also the SNR, that conditions the impact independently from the duration (as seen in Figure 3 with a short duration example and in Figure 4 with a long duration example). However, the study in this work is not concluding enough to set a rule for determining the impact by means of duration and SNR, despite it shows a clear relation of the impact in relation to these two variables and is useful to understand the nature of critical events in this dataset.

It has been concluded that the SNR measure may not be the optimum metric in long events, where the data used to compute the RTN energy would be far away from the surroundings of the ANE. This opens the door to new considerations of the SNR metric and new ways to avoid these biases. But no recorded ANEs decrease significantly the L_{A300s}, so, in the cases where the impact is low, rejecting a measure would not conclude in a significant alteration of the L_{A300s}.

Of the 4 h and 24 min total dataset, 20 min imply a bias to the RTN evaluation of the traffic noise level due to these four critical events. That is a bias of the 8% of the entire dataset only due to individual ANEs; other medium-impact ANEs recorded in the same time span could also alter the road-traffic noise level by more than 2 dB when aggregated. In the future, the impact of the aggregated ANEs found in each block of 5 min of audio signal will be deeply studied; it will probably lead us to consider lower impact ANE.

To summarize, this paper has studied the impact of the events non-related to traffic in a urban environment and has proven the need to remove them from the road-traffic noise map. Besides, an analysis of the impact in relation to SNR and duration is conducted, where it is concluded that the relation between both metrics and the impact is clear. Besides, if any health studies are conducted using noise maps, it is of paramount importance to detect and remove critical ANEs, as they bias significantly the L_{Aeq} measurement of road traffic, specially in urban environments. In further studies, other metrics and variables could be analyzed, including the ANE typology and saliency measurements focused to improve the SNR measure of long ANEs.

Acknowledgement

The research presented in this work has been partially supported by the LIFE DYNAMAP project (LIFE13 ENV/IT/001254). Ferran Orga thanks the support of the European Social Fund and the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement of the Catalan Government for the predoctoral FI grant No. 2018FI_B100175 and the support of the Doctorate Program in Information Technologies and the Application to Management, Architecture and Geophysics of La Salle - URL.

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