POLITECNICO DI TORINO

Master Degree in Mechanical Engineering

Study of the psychoacoustic parameters of the area surrounding a railway stopover: the case study of "Milano Martesana"

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SOMMARIO

1. Introduction

1.1 What is noise

Noise is a type of sound defined as unwanted, in fact there is no fixed value at which a sound is perceived as noise, and it could produce negative effects.

We can divide these effects in three main categories: damage – disturbance – annoyance.

With damage caused by noise we refer to the damages related to auditory apparatus or other pathological aspects and nowadays there are specific regulations in terms of limits in work environments.

The disturbance is about the interference with other sounds we want to listen to, the interference with sleep or the reduction of concentration. Also, for this problem some regulations are present in terms of environmental noise limits.

The feeling of annoyance can be attributed to a combination of noise and other factors, which together affects a series of problems related to the physical and psychological well-being of people.

Noise has the same physical meaning of the sound, to be precise, it is defined as a variation in oscillatory pressure propagating in an elastic medium. This variation is generated by the vibration of a mass that compresses and expands the medium in which it is located. In this case the mass is defined as a sound source or source of noise. To ensure that the sound level meter (the instrument by which noise is measured) measures sounds in the way that is most like that with which the human ear perceives them, a weighted curve of the various levels is used that attenuates the low and high frequencies. Noise levels measured using this weighing are expressed in dB(A). The dBA refers to the change in sound intensity level which takes into account the reduced sensitivity of the human ear at low frequencies, and it is based on the 40-phon curve on the equal-loudness contour of Fletcher-Munson curves.

As a vibrational phenomenon, noise is mainly described by two mean parameters: Amplitude (decibel dB) and Frequency (Hertz Hz).

To conclude, we consider various kind of noise:

- Continuous noise: the one from engine, heating systems and all those sources of noise, the variation in intensity of which does not exceed 3 dB.
- Intermittent noise: it is intermittent if its level varies rapidly. To give a few examples, we can refer to a helicopter passing over a house, a train, or an ambulance.

- Impulsive noise: it is referred to a noise with a high intensity and a duration less than 1 second.
- Low-frequency noise: it is the most typical noise because it is part of the daily soundscape and the most difficult to reduce at noise source. Low frequencies can spread for kilometers around. Low frequency noise is generally defined in a frequency range between 20 and 250 Hz.

1.2 Problem of railway noise pollution

Rail transport is considered as one of the most environmentally friendly, but the noise pollution caused by trains and railways is relevant.

In 2012 the Policy Department B (Structural and Cohesion Policies) has developed an interesting study about the railway noise pollution and the possibility to reduce it. The authors investigated in European Union with the help of the European Environment Agency (EEA) which compiled reports for all the Member States. According to the reports, they concluded that railway noise affects about 12 million inhabitants at daytime, with a noise exposure above 55 dB(A), and about 9 million at night-time with an exposure above 50 dB(A). The noise problem is concentrated in central Europe, where the train traffic is highest.

Talking about railways noise, it is not wrong to refer to noise annoyance, particularly when we consider noise interfering with sleep and so contributing to lower the quality of life. In fact, it is demonstrated that long-term exposure to transportation noise has been associated with cardiovascular disease, also causing diabetes and obesity. Some research has shown that noise annoyance leads to anger, disappointment, depression, anxiety and in general it negatively affects physical activity which is directly connected to the quality of life.

The three main noise sources are:

- Power equipment noise
- Rolling noise
- Aerodynamic noise

Engine noise is the most relevant because affects all diesel propulsion trains at every speed and electric trains at low speed. Rolling noise is always relevant but can become more significant when trains running in a not well-maintained infrastructure, or in a curve, when we could deal with squeal noise; the noise level coming from the interaction between wheel and rail is directly proportional to the speed, in fact if we double the velocity, we should have a noise level increase about 8-10 dB(A).

Finally, the aerodynamic noise is generated by the air flowing on the train' surface and by its discontinuity, it is principally related to the high-speed train when the velocity overtakes 270 km/h. The noise caused by pantograph is perceived when speed is higher than 200 km/h.

It is clear that the weight of a source with respect to another depends on the speed of the train.

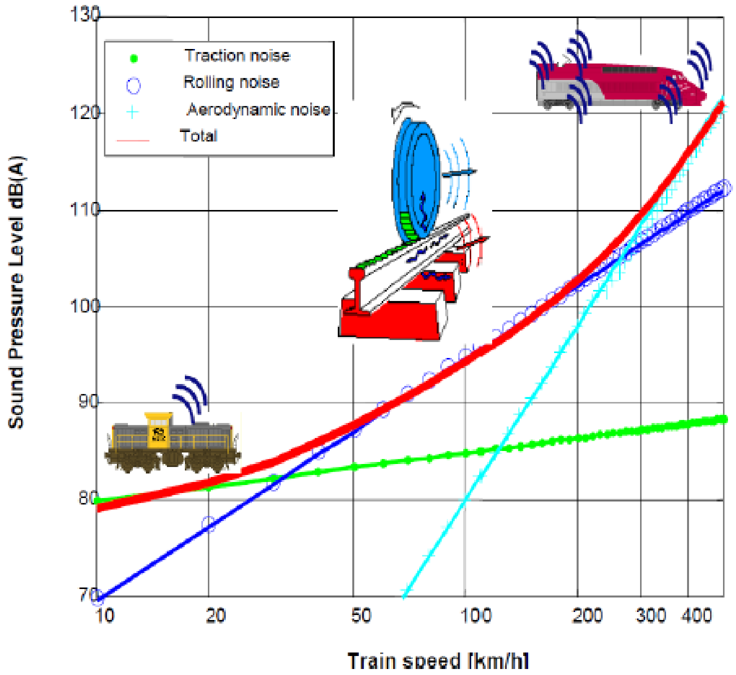

Figure 1: Relation between speed and noise source

In general, two types of measures are taken to reduce noise pollution: passive measures for places where noise is present, active measures applied directly to the source of noise. An example for the first ones could be the protection walls located between railway and houses; while the second solution could be choosing a different material for breaks (substituting cast iron with composite material), aerodynamic changes in pantograph designs, wheel absorbers, noise insulation of traction equipment exc…

According to Directive 2002/49/EC, all Member States provide to compute a noise maps and noise action plans. The survey led to these results, shared by the European Environment Agency (EEA) and the European Topic Centre on Land Use and Spatial Information (ETC LUSI).

The European Environment Agency (EEA) listed measures to avoid railway noise [Uwe Clausen, Claus Doll, Francis James Franklin, Gordana Vacis Franklin, Hilmar Heinrichmeyer, Joachim Kochsiek, Werner Rothengatter, Niklas Sieber. Reducing railway noise pollution. Directorate General for Internal Policies, Policy Department B: Structural and Cohesion Policies. 2012.], acting on some specific sources:

- Roughness-Induced rolling noise
- Wheel noise
- Rail noise
- Squeal noise
- High speed trains
- Other sources of noise

Roughness-Induced rolling noise: this problem of corrugation of rails and wheels can increase the ground vibrations and noise level by 20 dB. For such reason, there are many maintenance programmes related to rail and wheel quality.

Wheel noise: A European project was developed in order to reduce wheel noise, the result led to the following results. The aim is design more resilient wheels.

- Ring dampers reduce noise by 6 dB.
- Wheel-tuned absorbers reduce noise by up to 7 dB.
- Wheel web shields reduce noise by up to 9 dB.

Rail noise: most common solution is represented by noise barriers, but they have a large on-going maintenance cost, high visual impact and could create problems with the access to the track. An interesting alternative is the use of rail dampers.

Squeal noise: it is the high pitch noise (2-4 kHz) emitted in curves. Since lubrication plays an important role in reducing noise, as well as in controlling wear damages, the studies have been focused in lubricants applications.

High-speed trains: as mentioned before, noise caused by high-speed trains is relevant over 270 km/h, and the noise level could be like the rolling one. Pantographs generates a lot of noise and that problem can be reduced acting on aerodynamic design and materials, because pantographs are higher than noise barriers.

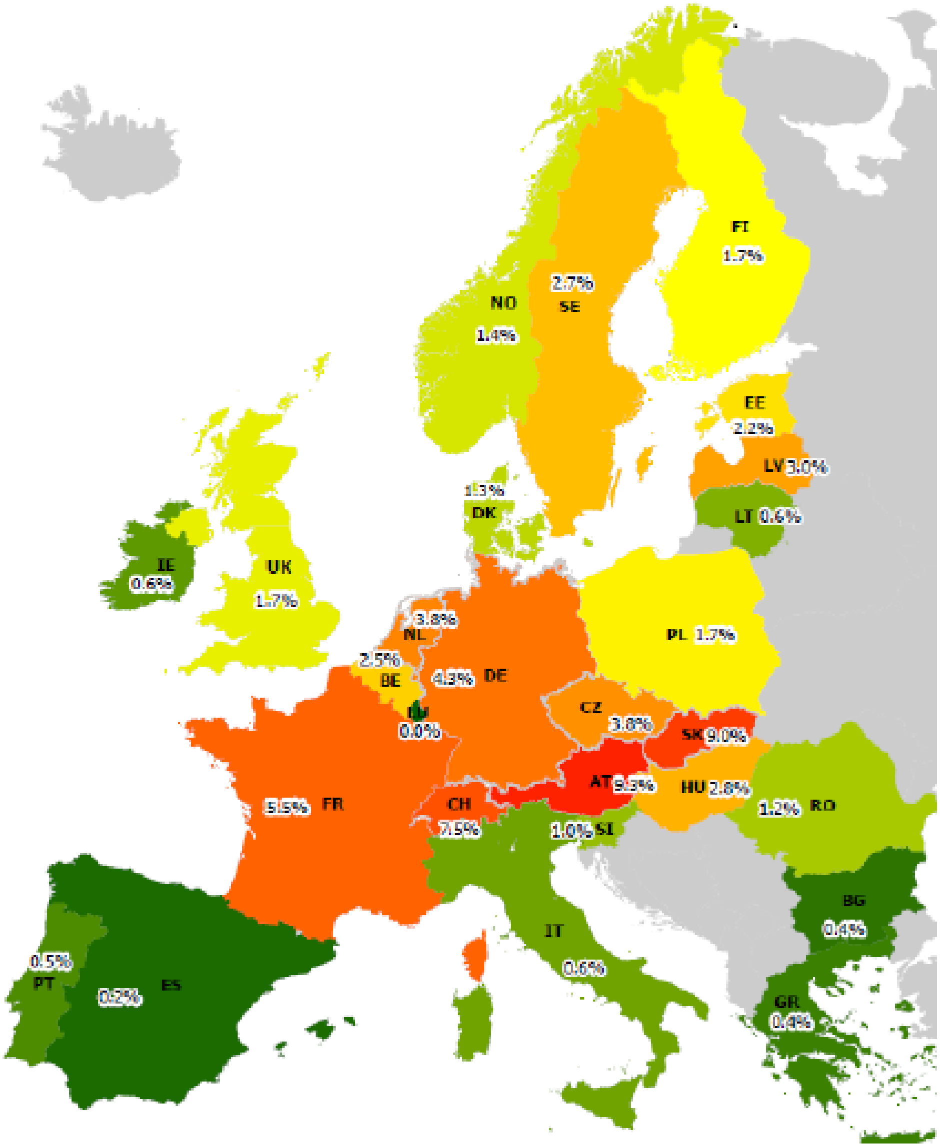

Figure 2: Share of population affected by railway noise Lden > 55 dB(A) in Europe inside and outside agglomeration areas 2010 - https://noise.eea.europa.eu/

As we can see in the previous picture, the following States are the most affected by railway noise with an L_{den} more than 55dB(A): Austria (9.3%), Slovakia (9.0%), Switzerland (7.5%), France (5.5%), Germany (4.3%), Czech Republic (3.8%), Netherlands (3.8%) and Latvia (3.0%).

Another interesting map can be found on the European Environment Agency website, where there is a precise distinction between daytime and night-time. On these pictures we can see how the railway noise is more concentrated in the Central Europe and United Kingdom, due to the higher number of railway links and the higher population density near the railways.

The following map shows the daytime data:

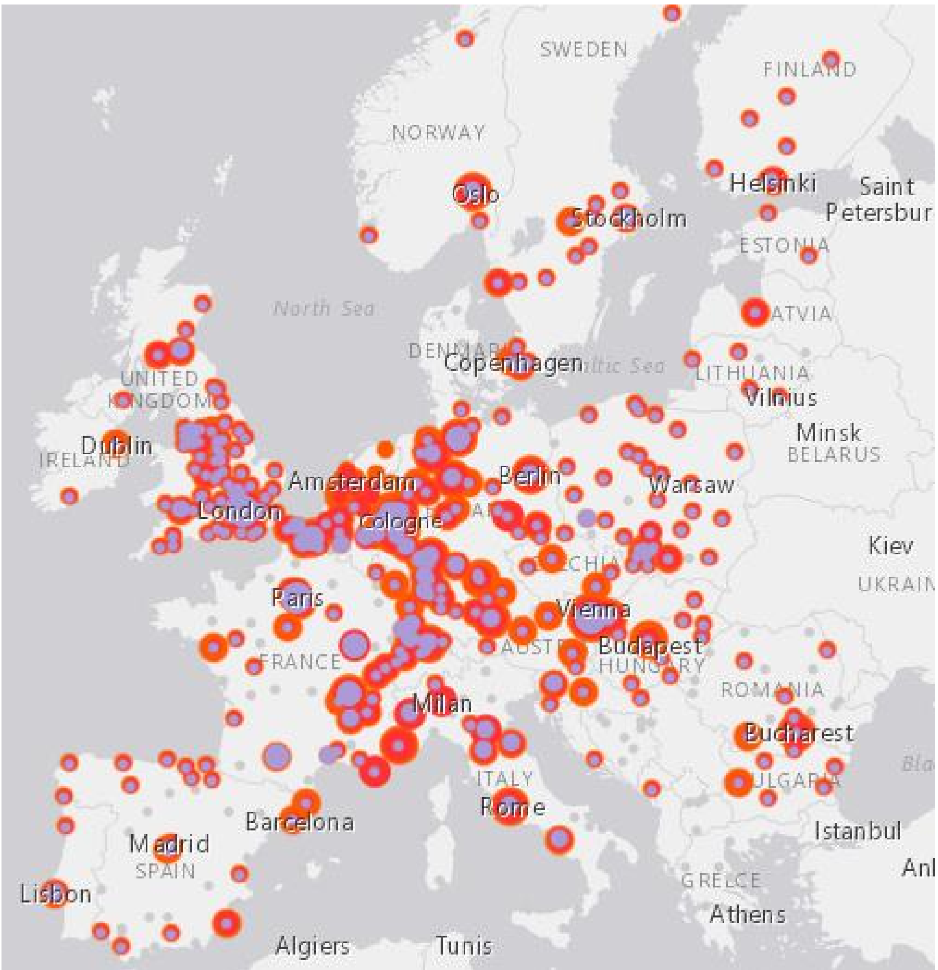

Figure 3: Concentration of noise exposure during daytime - https://noise.eea.europa.eu/

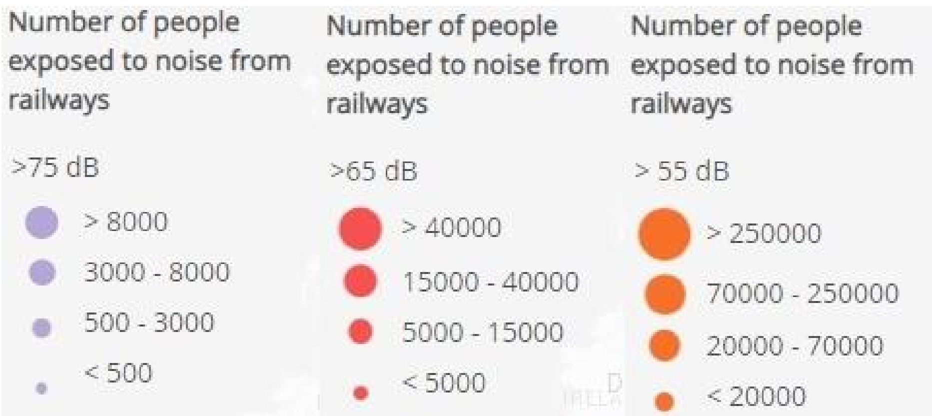

Figure 4: Reference values for Figure 3 - https://noise.eea.europa.eu/

The map which shows the night-time data is the following:

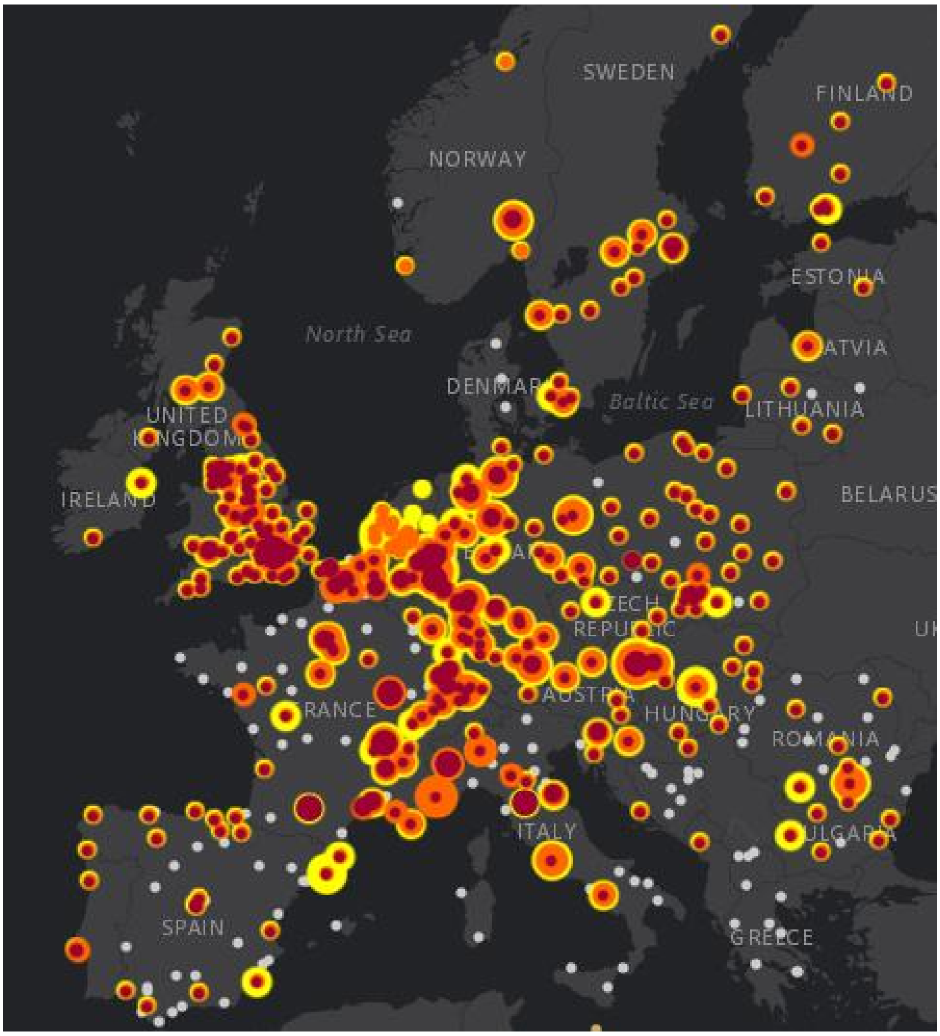

Figure 5: Concentration of noise exposure during night-time - https://noise.eea.europa.eu/

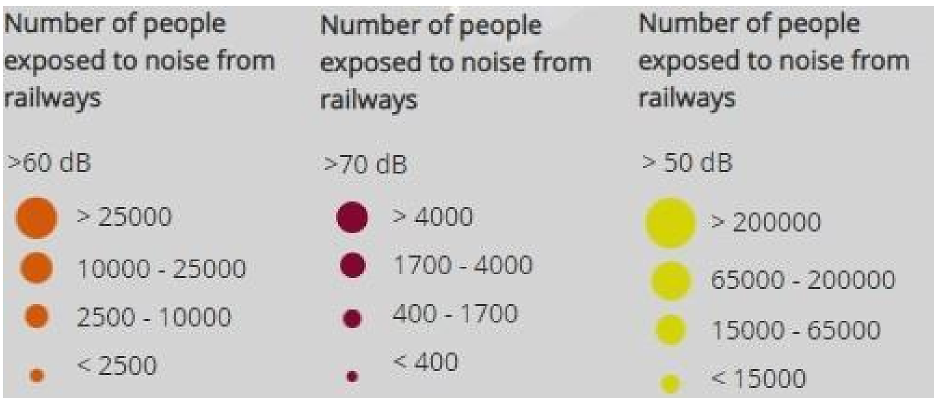

Figure 6: Reference values for Figure 5 - https://noise.eea.europa.eu/

1.3 Environmental noise directive 2002/49/EC

Directive 2002/49/EC came into force in Italy on 2005 with the “Decreto legislativo 19 agosto 2005 n.194”. The Environmental Noise Directive propose four fundamental objectives:

- “Monitoring the environmental problem; by requiring competent authorities in Member States to draw up ‘strategic road maps’ for major roads, railways, airports and agglomerations, using harmonised noise indicators L_{den} (day-eveneing-night equivalent level) and L_{night} (night equivalent level). These maps will be used to assess the number of people annoyed and sleep-disturbed respectively throughout Europe”
- “Informing and consulting the public about noise exposure, its effects, and the measures considered to address noise, in line with the principles of the UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, known as the Aarhus Convention, and signed on June 25,1998”
- “Addressing local noise issues by requiring competent authorities to draw up action plans to reduce noise where necessary and maintain environmental noise quality where it is good. The Directive does not set any limit value, nor does it prescribe the measures to be used in the action plans, which remain at the discretion of the competent authorities”.
- “Developing a long-term EU strategy, which includes objectives to reduce the number of people affected by noise in the longer term and provides a framework for developing existing Community policy on noise reduction from source. With this respect, the Commission has made a declaration concerning the provisions laid down in article 1.2 regarding the preparation of legislation relating to sources of noise”.

According to the Directive 2002/49/EC, all Member States have to provide noise maps and action plans for noise reduction. This Directive provides the following formula to calculate the relevant day-evening-night level:

$$L_{den} = 10log\frac{1}{24}\left(12 * 10^{\frac{L_{day}}{10}} + 4 * 10^{\frac{L_{evening}+5}{10}} + 8 * 10^{\frac{L_{night}+10}{10}}\right)$$

Where:

- L_{day} is the A-weighted long-term average sound level as defined in ISO 1996-2 1987, determined over all the day periods of a year.
- $L_{evening}$ is the A-weighted long-term average sound level as defined in ISO 1996-2 1987, determined over all the evening periods of a year.

- L_{night} is the A-weighted long-term average sound level as defined is ISO 19962 1987, determined over all the night periods of a year.
- L_{den} is the average noise level for a period of 24 hours.

In which the day is 12 hours, the evening is 4 hours, and the night is 8 hours. The Member States can shorten the evening period by one or two hours and modify day or night period accordingly, and this change must be the same for all the sources.

On the 4th of March 2020 there was a modify of the Attachment III in Directive 2002/49/EC, approved with Directive 2020/367. This Attachment concerns methods to determining harmful effects. The latter are:

- Ischaemic heart disease (IHD), recognized by the WHO with codes from BA40 to BA6Z
- High annoyance (HA)
- High sleep disturbance (HSD)

On the following formulas, AR means *absolute risk* while RR means *relative risk*.

IHD formula:

$$RR_{IHD,i,road} = e^{\left(\frac{\ln(1.08)}{10}\right)*L_{den}-53)} \text{ when } L_{den} \text{ is over 53 dB, otherwise } RR_{IHD,i,road} = 1$$

HA formulas:

$$AR_{HA,road} = \frac{78.9270-3.1162*L_{den}+0.0342*L_{den}^2}{100} \text{ (for road traffic noise)}$$

$$AR_{HA,rail} = \frac{38.1596-2.05538*L_{den}+0.0285*L_{den}^2}{100} \text{ (for rail traffic noise)}$$

$$AR_{HA,rail} = \frac{-50.9693+1.0168*L_{den}+0.0072*L_{den}^2}{100} \text{ (for airplane traffic noise)}$$

HSD formulas:

$$AR_{HSD,road} = \frac{19.4312-0.9336*L_{night}+0.0126*L_{night}^2}{100} \text{ (for road traffic noise)}$$

$$AR_{HSD,rail} = \frac{67.5406-3.1852*L_{night}+0.0391*L_{night}^2}{100} \text{ (for rail traffic noise)}$$

$$AR_{HSD,air} = \frac{16.7885-0.9293*L_{night}+0.0198*L_{night}^2}{100} \text{ (for airplane traffic noise)}$$

1.4 D.p.c.m. 14 novembre 1997 – Determinazione dei valori limite delle sorgenti sonore (determination of the limit values of sound sources)

This Law determines emission limit values, entry limit values, attention values and quality values.

Fixed sound sources: the technical installations of buildings and other installations combined with buildings also on a transitional route whose use produces noise emissions; road, rail, airport, maritime, industrial, craft, commercial and agricultural infrastructure; wind farms; parking spaces; areas used for freight handling plants; the storage of means of transport of persons and goods; sports and recreational areas.

Moving sound sources: all the sound sources not above-mentioned.

Emission limit value: the maximum noise value that can be emitted by a sound source, measured near the source itself.

Intake limit value: the maximum noise value that can be input from one or more sound sources into the living environment or external environment, measured near the receivers. These are distinguished into:

- Absolute limit values, determined by reference to the equivalent level of ambient noise.
- Differential limit values, determined by reference to the difference between the equivalent level of ambient noise and residual noise.

Differential entry limit value: the maximum variation in sound levels resulting from a specific source, measured in living environments. The excess of ambient noise (background noise plus that due to the new disturbing source) over residual noise (background noise, without the new disturbing source), must be less than:

- 5 dB for the daytime reference time (from 6:00 am to 10:00 pm)
- 3 dB for the night-time reference time (from 10:00 pm to 6:00 am)

The verification of compliance with these limits is provided for by measures within living environments with open and closed windows.

Attention value: the input value, independent of the type of source and the acoustic classification of the territory of the area to be protected, the overcoming of which obliges an acoustic mitigation intervention and makes applicable, where the conditions are fulfilled, the actions declared in "articolo 9 legge 26 ottobre 1995 n. 447, modifiche introdotte dal DLgs 42 del 17 febbraio 2017".

Quality value: the noise values to be achieved in the short, medium and long term with the available technologies and methods of remediation, in order to achieve the protection objectives laid down in this Law: “legge 26 ottobre 1995 n. 447, modifiche introdotte dal DLgs 42 del 17 febbraio 2017”.

Acoustic classification: the result of the division of the urbanized territory into homogeneous acoustic areas. Acoustic zoning is a technical-political document of the governance of the territory, as it regulates its use and binds the methods of development of activities. The aim is to prevent the deterioration of unpolluted areas and to provide an indispensable tool for planning, preventing, and restoring urban, commercial, craft and industrial development.

There are six class of subdivision:

- CLASS I: particularly protected areas: this class includes areas where quiet is a basic element for their use: hospital, school, areas intended for leisure, rural residential areas, areas of urban interest, public parks, etc.
- CLASS II: areas intended for mainly residential use: this class includes the areas mainly affected by local vehicular traffic, with low population density, with limited presence of commercial activities and absence of industrial and craft activities.
- CLASS III: mixed-type areas: urban areas affected by local or crossing vehicle traffic fall into this class, with medium population density, with the presence of offices with limited presence of craft activities and with no industrial activities; Areas rural areas affected by activities using operating machines.
- CLASS IV: areas of intense human activity: this class includes urban areas affected by heavy vehicular traffic, with high population density, with high presence of commercial activities and offices, with the presence of craft activities; areas close to high-communication roads and railway lines; port areas, areas with limited presence of small industries.
- CLASS V: predominantly industrial areas: this class includes areas affected by industrial settlements and with a shortage of houses.
- CLASS VI: exclusively industrial areas: this class includes areas exclusively affected by industrial activities and without housing settlements.

The law provides that the input limits are determined according to the type of source, the time of day and the intended use of the area to be protected but does not indicate its value.

Valori (dBA)	Tempi di Riferim.[1]	Classi di Destinazione d'Uso del Territorio					
		I	II	III	IV	V	VI
Valori limite di emissione (Art. 2)	Diurno	45	50	55	60	65	65
	Notturno	35	40	45	50	55	65
Valori limite assoluti di immissione (Art. 3)	Diurno	50	55	60	65	70	70
	Notturno	40	45	50	55	60	70
Valori limite differenziali di immissione [2] (Art. 4)	Diurno	5	5	5	5	5	-[3]
	Notturno	3	3	3	3	3	-[3]
Valori di attenzione riferiti a 1 h (Art. 6)	Diurno	60	65	70	75	80	80
	Notturno	45	50	55	60	65	75
Valori di attenzione relativi a tempi di riferimento (Art. 6)	Diurno	50	55	60	65	70	70
	Notturno	40	45	50	55	60	70
Valori di qualità (Art. 7)	Diurno	47	52	57	62	67	70
	Notturno	37	42	47	52	57	70

Figure 7: Limit values of noise sources according to DPCM 14 novembre 1997

1.5 D.p.r. 18 novembre 1998 – Norme in materia di inquinamento acustico da traffico ferroviario (regulations about the noise pollution caused by railway traffic)

<u>Newly built railways with design speeds of more than 200 km/h</u>

Within the railway area (250 m measured by the centre of the external tracks and on each side), the absolute limit values for the input of the noise produced are as follows:

- 50 dB(A) Daytime leq, 40 dB(A) Night leq for schools, hospitals, nursing and nursing homes
- 65 dB(A) Daytime leq, 55 dB(A) Night leq for other receivers

<u>Existing and newly built railways with project speeds not exceeding 200 km/h</u>

Within the railway area, the absolute limit values for the entry of the noise produced are as follows:

- 50 dB(A) Daytime leq, 40 dB(A) Night leq for schools, hospitals, nursing and nursing homes
- 70 dB(A) Daytime leq, 60 dB(A) Night leq for other receivers within the relevant BAND A (100 m measured from the centre line of the outer tracks and on each side)

65 dB(A) Daytime leq, 55 dB(A) Night leq for other receivers within the relevant BAND B (100 to 250 m from the centre of the outer tracks and on each side).

1.6 Case study – Railway stopover Milano Martesana

The acoustics and psychoacoustics recordings were done at the railway stopover Milano Martesana. The area of interest in shown below and we focused the measurements on the right side considering the exposition of the houses to the noise. If we look at the picture, we can see that trains are on both sides but, on the left one, they are in a closed space and so noise is reduced by such structures. On the right side of the stopover, houses and buildings such school and library are directly exposed to the noise produced by train. Even if trains are stopped waiting for the next race, their engines are kept on so as not to interrupt internal system like the cooling or heating one. Another important point of registration is the entrance of the stopover because in this site also squeal noise contributions to characterize the whole environmental noise.

Figure 8 railway stopover Milano Martesana from Google Maps

2. Acoustic and psychoacoustic

2.1 Physics of sound

As mentioned in the previous chapter, noise is just an unwanted sound and for this reason it has the same physics characteristics by which it is analysed. The fundamental characteristics are amplitude, frequency, and wavelength. Sound propagates with its own velocity which is described by this formula:

$$v = \sqrt{\frac{k}{\rho}\,p}$$

Where:

k is the adiabatic compressibility factor.

ρ is the density.

p is the pressure.

At the temperature equals to 20°C, the speed of sound is about 343 m/s. In solid means, the previous formula is used substituting the compressibility factor with the Young Modulus *E*.

Amplitude: it is the maximum value of the wave, precisely the distance between.

Wavelength: it is the distance between two crests.

Frequency (f): it is the number of the periodic events in a second and it is measured in Hertz (Hz).

Period (T): it is the invers of frequency, time to have a complete oscillation.

They are bond with speed of sound and wavelength by these formulas:

$$\lambda f = c \qquad ; \qquad T = \frac{1}{f}$$

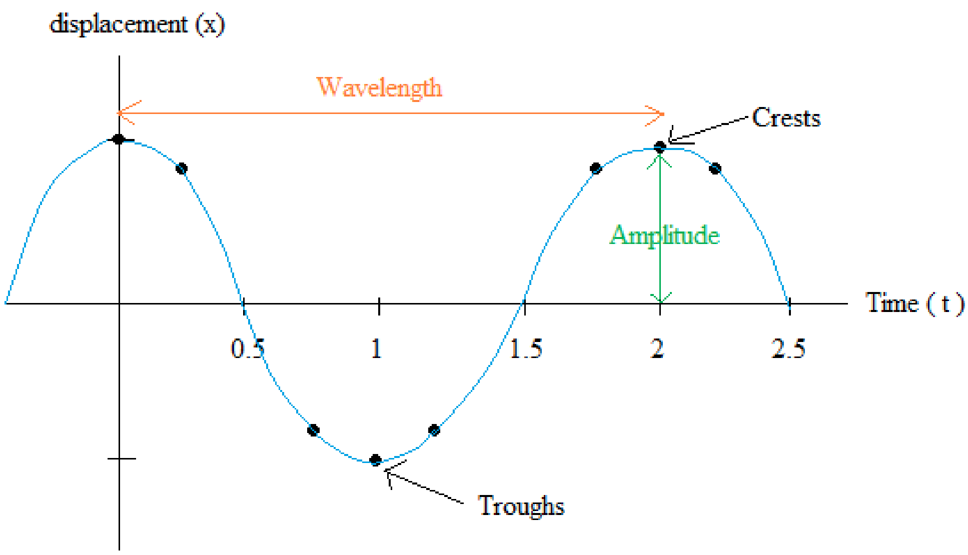

Figure 9 Description of a waveform

At that point it is useful to give a definition of Pure Tone as a sinusoidal soundwave, which is mathematically represented by the function $y = Asen(2\pi ft)$. We can approximately say that diapason is an instrument which emits a pure tone. In reality there are no sound sources which are able to propagate a pure tone, but they produce other vibrations named harmonics. The harmonics are characterised by frequencies which are multiple of the main frequency, also called *fundamental frequency*.

2.2 Introduction to psychoacoustics

Psychoacoustics studies how the human auditory system perceives and reacts to the acoustics stimuli. This is a sub-field of the Psychophysics and investigates the physiological and psychological patterns related to the auditory perception.

The auditory field: it is the field in which sounds can be heard by human ear. On the y-axes there are dB values from 0 to 140, whereas on x-axes there are frequencies from 15-20 Hz to 20kHz, which is the approximated interval where we can hear. The space is more precisely delimited by two curves, the upper one representing the pain threshold and the lower one representing the audibility threshold.

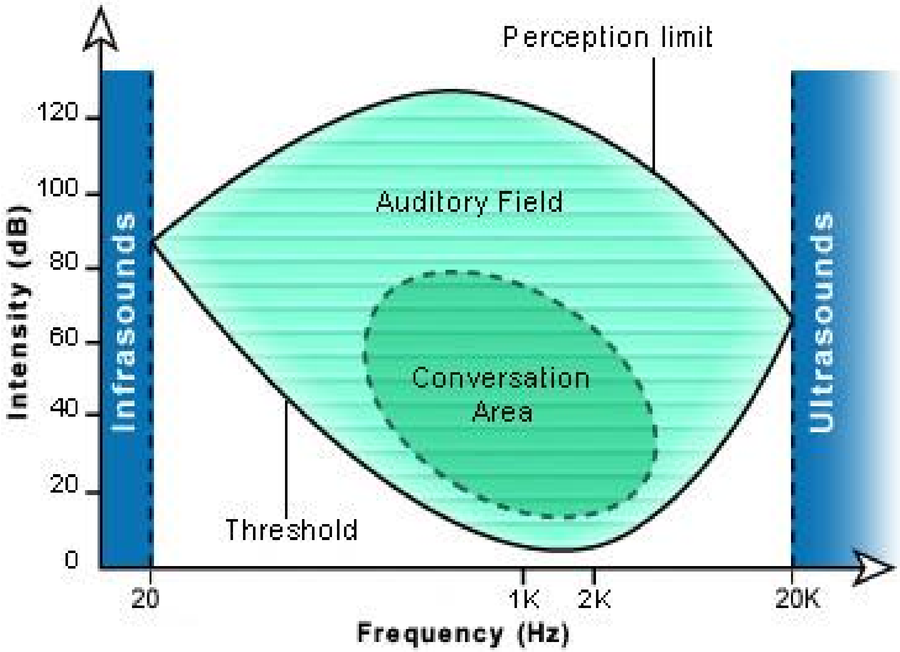

Figure 10 Diagram of Auditory Field

Our brain is able to perceive a frequencies range between 20 and 20'000 Hz, all frequencies under 20 Hz are called *infrasound* and the ones over 20 kHz *ultrasounds*. We have to specify that consideration is not a rule, in fact young people can hear high frequencies better than the older ones. To be precise, this frequency range is not always audible at the same volume, so we introduce the Fletcher-Munson curves, also known as *equal-loudness contours*. They describe the perceived loudness of a sound in relation to its frequency for human listeners by using steady pure tones for their experiments; it is not an exact reproduction of the ear's behaviour, but an average resulting from experimental measurements done over many people without auditory problems. Each curve identifies a group of frequencies and intensity level which are perceived by brain at the same loudness.

Fletcher-Munson diagram is shown in Figure 11:

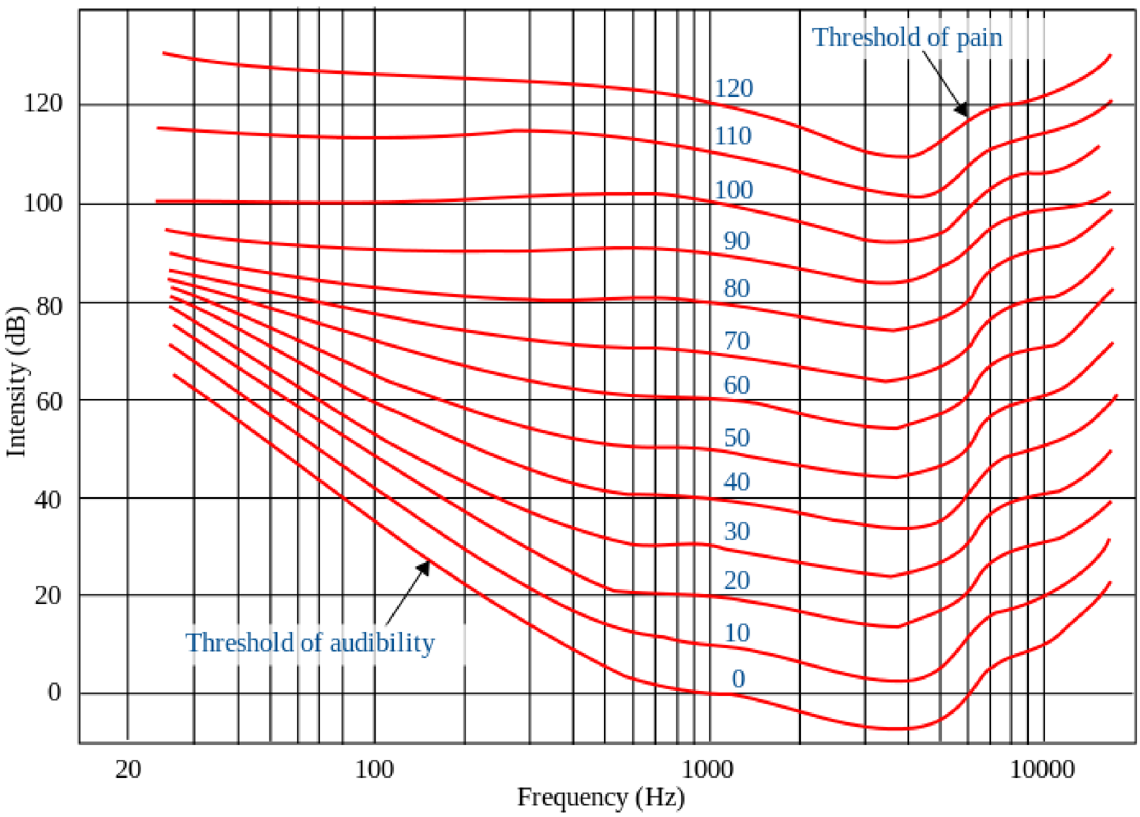

Figure 11 Feltcher-Munson Diagram

Weighting curves

To perform reliable noise measurements, we must adopt tools that emulate the characteristic of the human ear. Because the auditory response is different depending on frequency and intensity, weighting curves A, B, C, and D are used to simulate this characteristic. To have a decent representation of the human sensation we have then to apply a weighting curve, which is equivalent to placing a filter on the input signal. This filter has characteristics that derive from the analysis of equal-loudness curves.

The A-weighting curve approximates the inverse of the 40 phon equal-loudness curve and it is used for levels below 60 dB. It is currently the most widely used curve. A-weighted SPL is easy to calculate and is readable in most of sound level meters.

The B-weighting curve approximates the inverse of 70 phon equal-loudness curve and it was used for levels between 60 and 80 dB. Nowadays it is not used.

The C-weighting curve derives from 100 phon equal-loudness curve and it is used for level over 80 dB. It shows a flat and linear behaviour on the central part.

The D-weighting curve was used for very high noise, for example the one generated by airplanes. Currently it is not used.

The Z-weighting curve is a flat frequency response between 10 Hz and 20 kHz ± 1.5 dB.

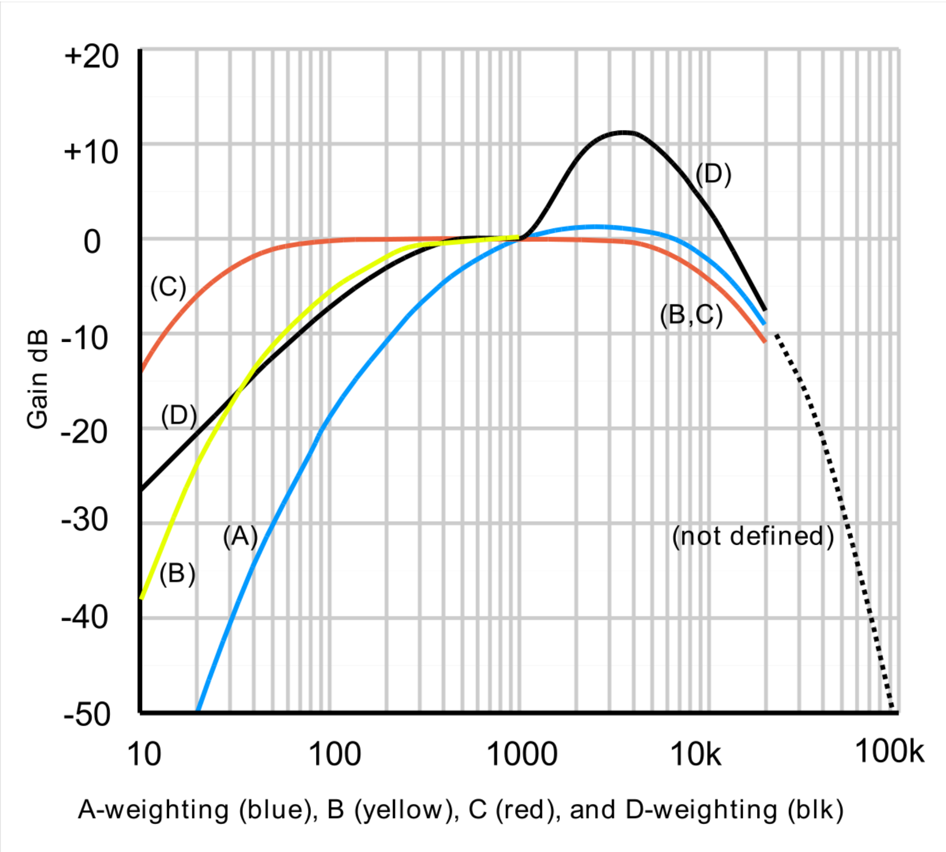

Figure 12 Weighting curves

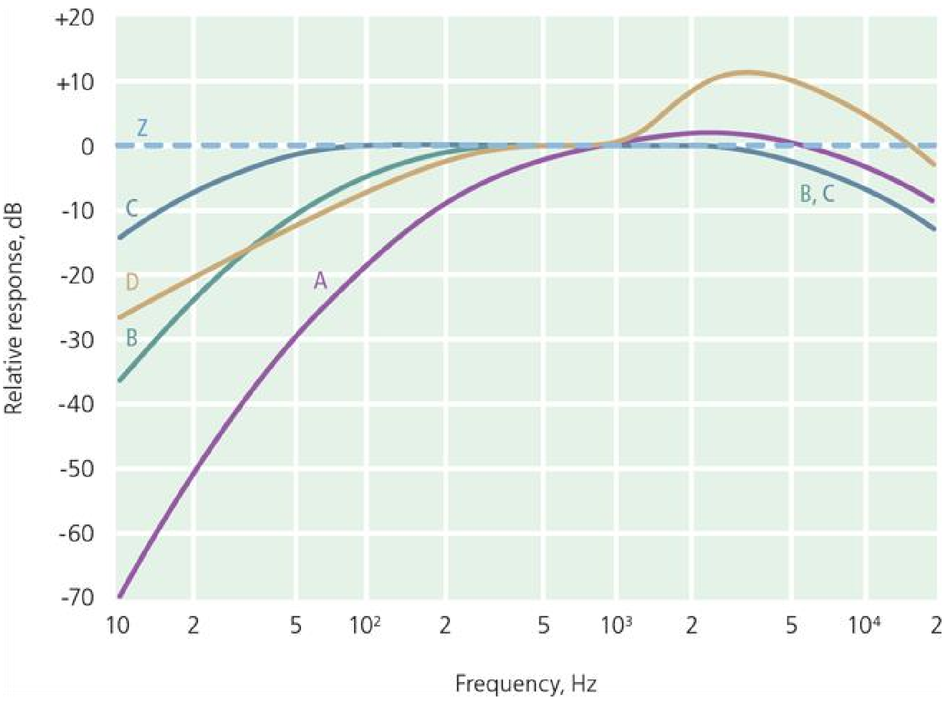

Figure 13 Weighting curves including Z-curve

Frequency [Hz]	A-Weighting	C-Weighting	Z-Weighting
8	-77.8	-17.7	0.0
16	-56.7	-8.5	0.0
31.5	-39.4	-3.0	0.0
63	-26.2	-0.8	0.0
125	-16.1	-0.2	0.0
250	-8.6	0.0	0.0
500	-3.2	0.0	0.0
1000	0	0	0
2000	1.2	-0.2	0.0
4000	1.0	-0.8	0.0
8000	-1.1	-3.0	0.0
16000	-6.6	-8.5	0.0

Figure 14 Values of weighting curves

2.3 Decibel

The unit measure decibel (dB) is used to represent the "level" of a certain quantity with respect of its own reference value. The formula of such calculation is the following:

$$L_x = 10\log\left(\frac{x}{x_0}\right)$$

Where x represents the quantity of interest and x_0 its reference value.

Now we introduce the main logarithmic functions for the acoustic and psychoacoustic field.

Sound Pressure Level (SPL): $SPL = 10\log\left(\frac{P}{P_0}\right)^2 \;\; or \;\; SPL = 20\log\left(\frac{P}{P_0}\right)$

Where P_0 is the reference sound pressure equal to $2 * 10^{-5}\ Pa$

Acoustic Intensity Level: $L_I = 10\log\left(\frac{I}{I_0}\right)$

Where I_0 is equal to $10^{-12} W/m^2$

Acoustic Power Level: $L_W = 10\log\left(\frac{W}{W_0}\right)$

Where W_0 is equal to $10^{-12} W$

The environmental noise laws and regulations do not propose limit values about psychoacoustic parameters. Analysing them could be very useful to investigate noise annoyance, since the latter depends on many aspects as the physical characteristics, the psychoacoustic ones, and psychological factors. Some research and projects (which examine noise annoyance) compute acoustic and psychoacoustic analysis and produce some questionnaires to be compiled by the inhabitants living around the area on which noise effects are studied.

2.4 Psychoacoustic parameters

Loudness

This parameter represents the perception of sound pressure as the magnitude of an auditory sensation. In other words, it is a subjective measure of perceived sound intensity. Such perception depends on SPL (sound pressure level), frequency and waveform of a sound. The unit measure of Loudness (N) is the *sone.* A sone is defined as the loudness heard by typical listeners when confronted with a 1000 Hz tone at a Loudness level (L_N) of 40 phons. Loudness describes the absolute sensation of a sound strength perceived by humans under specific listening conditions, instead the Loudness level describes the relative sensation. There are many factors influencing loudness as duration of a sound, predictability, and fatigue. Loudness of an unexpected sound is higher than the one of an expected sound. Moreover, if we expose ears to an intense sound, the hearing threshold could increase due to fatigue.

Looking at the equal-loudness contours diagram, above threshold, for a given increase in sound level the impression of loudness increases faster at low frequencies than at higher frequencies. In this case study we had extracted loudness values calculated both by Zwicker's method and Stevens' method. Zwicker's method accounts for both the changes with frequency in sensitivity at threshold and the rates at which increasing levels contribute to the impression of loudness.

Roughness

Roughness describes the subjective perception of fast amplitude modulation (between 20 and 300 Hz). The unit measure of roughness is the *asper*. An asper is defined as the roughness produced by a 1000 Hz tone of 60 dB modulated by 70 Hz sine wave and a modulation factor if 1 (100%).

Sharpness

Sharpness describes the perception of timbre (also called tone colour), depending on the spectral envelope of the sound. It is the measure of the high frequencies contained in a sound, the higher the number of high frequencies the higher the sharpness. The unit measure is the *acum*. An acum is defined as a narrow band noise one critical band wide at a centre frequency of 1000 Hz having a level of 60 dB. To conclude, sharpness represents the comparison between the amount of the high frequency energy and the total energy. Sounds with greater high-frequency content are described by listeners as having a sharper timbre. The sharpness that has been standardized (DIN 45692, 2009) is referred to the loudness based on Zwicker's method.

Fluctuation Strength

The Fluctuation strength is similar to the roughness, but it describes the perception of amplitude modulation up to 20 Hz. The unit measure of fluctuation strength is the *vacil*. A vacil corresponds to the fluctuation strength produced by a tone of 1000 Hz and 60 dB which is 100% amplitude modulated at 4 Hz.

Booming

The parameter Booming is practically defined as the opposite of Sharpness, since it is a measure of the low frequencies content of a sound.

Tonality

Tonality is a metric expressing the relative weight of the tonal components in a given noise spectrum. Its calculation is based on a comparison between the amplitude of the tonal component and the amplitude of the noise at the neighbouring frequencies.

Pitch

Pitch characteristic is strictly related to the frequency and permits us to classify a sound as “low” or “high”. This parameter depends on intensity level, duration and also diplacusis.

Intermittency Ratio (IR)

It is the ratio between the sound energy contribution of events, and the overall contributions during the measurements period. It expresses the energetic share of noise exposure created by individual noise events. The intermittency index was introduced to study the variability of noise exposure from transport infrastructure, taking into account both the number and the typology of noisy events over a period of time.

Here is the formula to compute that index:

$$IR\% = \left(\frac{10^{0.1-L_{eq,T,Events}}}{10^{0.1*L_{eq,T,tot}}}\right) * 100$$

Where:

$L_{eq,T,tot}$ is the Equivalent Continuous Sound Pressure Level.

$L_{eq,T,Events}$ is the Equivalent Continuous Sound Pressure Level for Events, it includes all sound energy contributions which overtake a fixed threshold enough distant from background noise. Such threshold (K) is determined as follows: $K = L_{eq,T,tot} + C$, where C falls between 0 and 10 dB.

2.5 Binaural recording

Binaural recording provides all the dimensions in which sound propagates, as well as a more precise tone. This is possible thanks to its main feature: there are two input listening signals, one for each ear. For this reason, we talk about "binaural", because when an audio recorded with this technique is played, you have the feeling of being present at the place of recording, at the moment it was made.

This technique requires a particular microphone, so a different instrument from the phonometer. The peculiarity of binaural recording concerns the headset: this technique is very related to how the human feels. The human ear has the function of geolocating the sound source, equalizing and processing sounds in real time, using the brain. Usually, a copy of the human head is used, faithfully reproduced in all its anatomical characteristics. This reproduction of human head is also called *DUMMY HEAD RECORDING* and it is designed considering the average dimensions of human head and it contains two microphones within the ears.

One of the most important problems that arises with this type of technique concerns frontal localization. It often happens that the sound sources placed in the listener's frontal hemisphere seem to come from the back area or seem closer than the actual distance. The main cause concerns the anatomy of the ear: each pinna has its own shape and therefore each has its own anatomical model of localization. Another reason may be that we often use minimal head movements to locate the location of the sound source. This is possible due to the different sound pressure exerted in the two eardrums, a difference that allows the brain to localize the source.

Two pictures of instruments used to make binaural recordings are following:

Figure 15 Dummy head for binaural recording.

Figure 16 Dummy head designed by 3DIO.

3. Noise measurements

3.1 Instrument and modality for binaural recording

Instruments generally used for binaural recording are those mentioned before, but in our case, we employed a particular kit of tools produce by SIEMENS including LMS 3D Binaural Headset, tablet and LMS SCADAS XS System.

The main characteristic of binaural recording headphones (LMS 3D Binaural Headset) is having two microphones per ear. Such equipment permits to record the sounds around us and, once someone wants to reproduce it, we have the sensation to be in the place in which recordings were done.

Figure 17 Headphone for binaural recording

LMS SCADAS System is a data acquisition unit to which a binaural headset is attached by means of a specific wire, then we connect such device with a tablet, in which there is an application called LMS Smart Scope. The latter is used to start, stop, and manage recordings. Through a wireless connection, this app allows on-the-go data monitoring and validation, flip through existing measurement setups, or create a new configuration from scratch.

Figure 18 Siemens device for binaural recording

Even if binaural recordings are usually taken leaving a dummy head fixed in a precise point, we have adopted another modality: walking around the point of interest, to record and investigate how perception varies with distance and direction of the noise source.

We selected five most critical points, showed in the following picture, and for each point we made one or more recordings with a duration about 10 minutes.

Figure 19 Milano Martesana stopover from Google Maps

3.2 Position 1

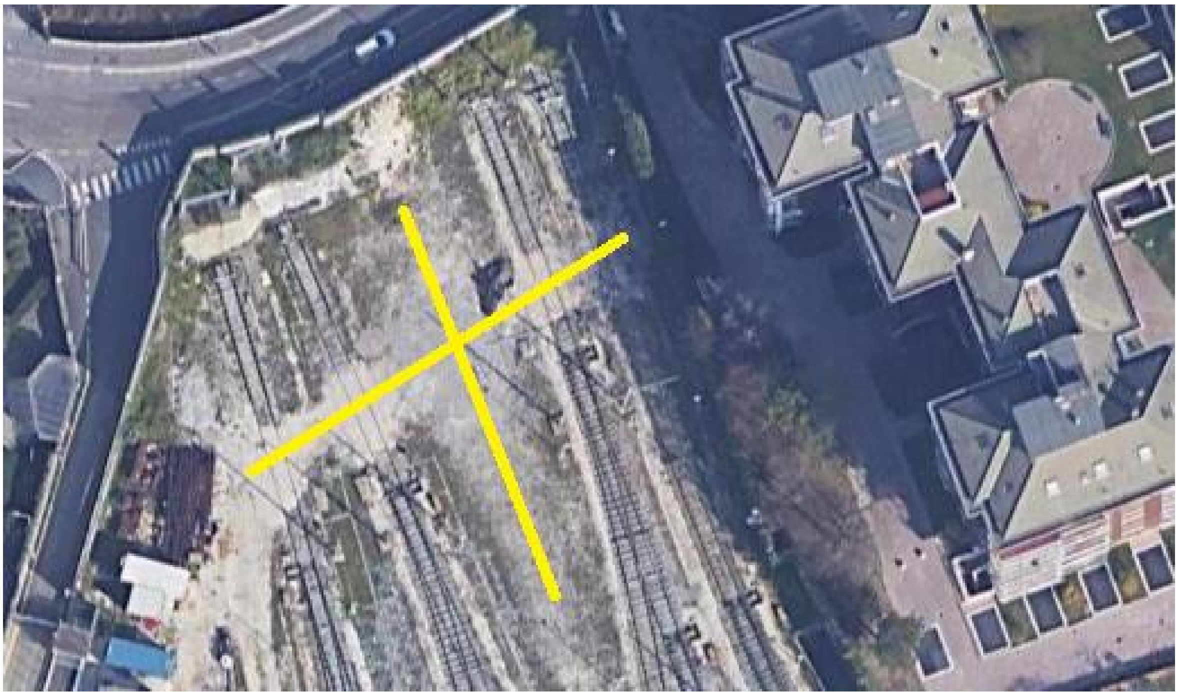

Figure 20 Position n.1 from Google Maps

The first point we consider of interest is the one zoomed in the above picture. We wanted to evaluate psychoacoustic parameters at the end of the rail to investigate how the inhabitants (on the right side of the picture) perceive noise and if the road noise is more relevant than the railway one. Yellow line represents the walking movements during the binaural recordings. The displacement is designed to capture noise moving away and approaching from the houses and from the road. Parameters individuated here are used as reference values for the "silence condition". Before carrying out the analysis it was necessary to listen to the recording and highlight the time intervals useful for the study of the parameters. This procedure has been done because of the strong wind that disturbed the listening, so not all the recording was useful for the analysis. In this record we do not have time intervals longer than three seconds without contribution of wind or the sound of shoes on stones and grass.

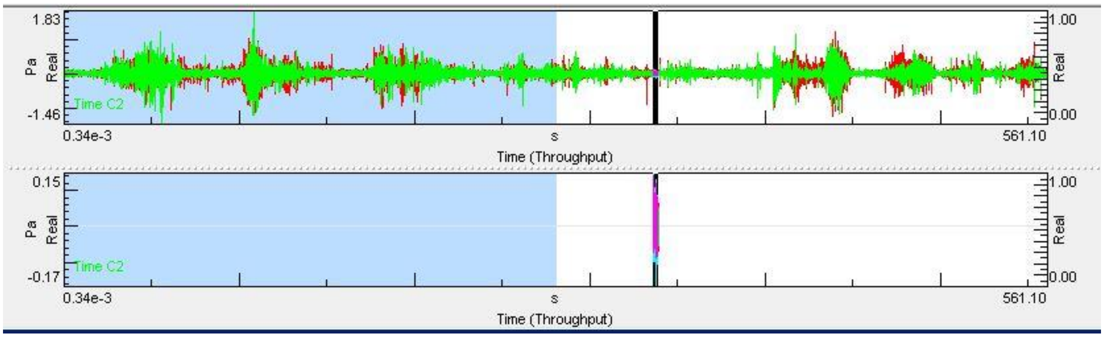

Figure 21 Time interval highlighted.

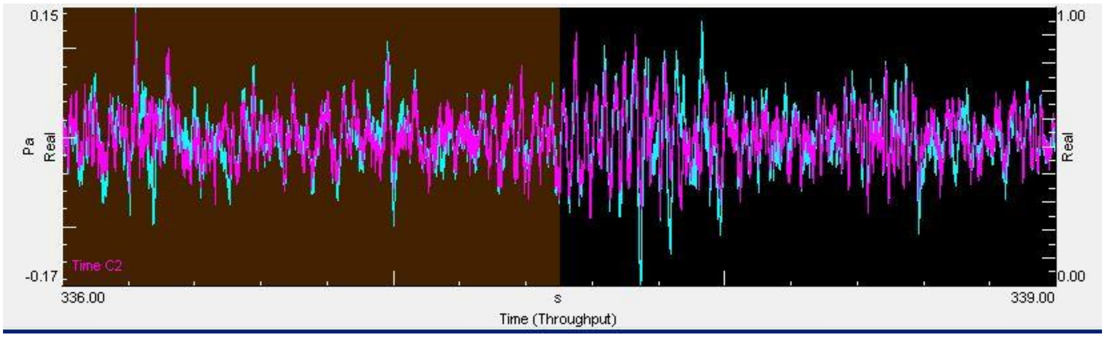

Figure 22 Zoom of the selected time interval.

Figure 23 Detail of Position n. 1

Figure 24 Detail of Position n. 1

Coordinates	**45.510777253896315, 9.216408300422609**
Noise sources	**The main source is road traffic, lower contributions of trains**
Buildings	**Houses very close to Position 1**
Number of records	**1**
Duration of records	**10 min**
Time Frame 1	**1:09 – 1:12**
Time Frame 2	**2:20 – 2:23**
Time Frame 3	**5:36 – 5:39**

3.3 Position 2

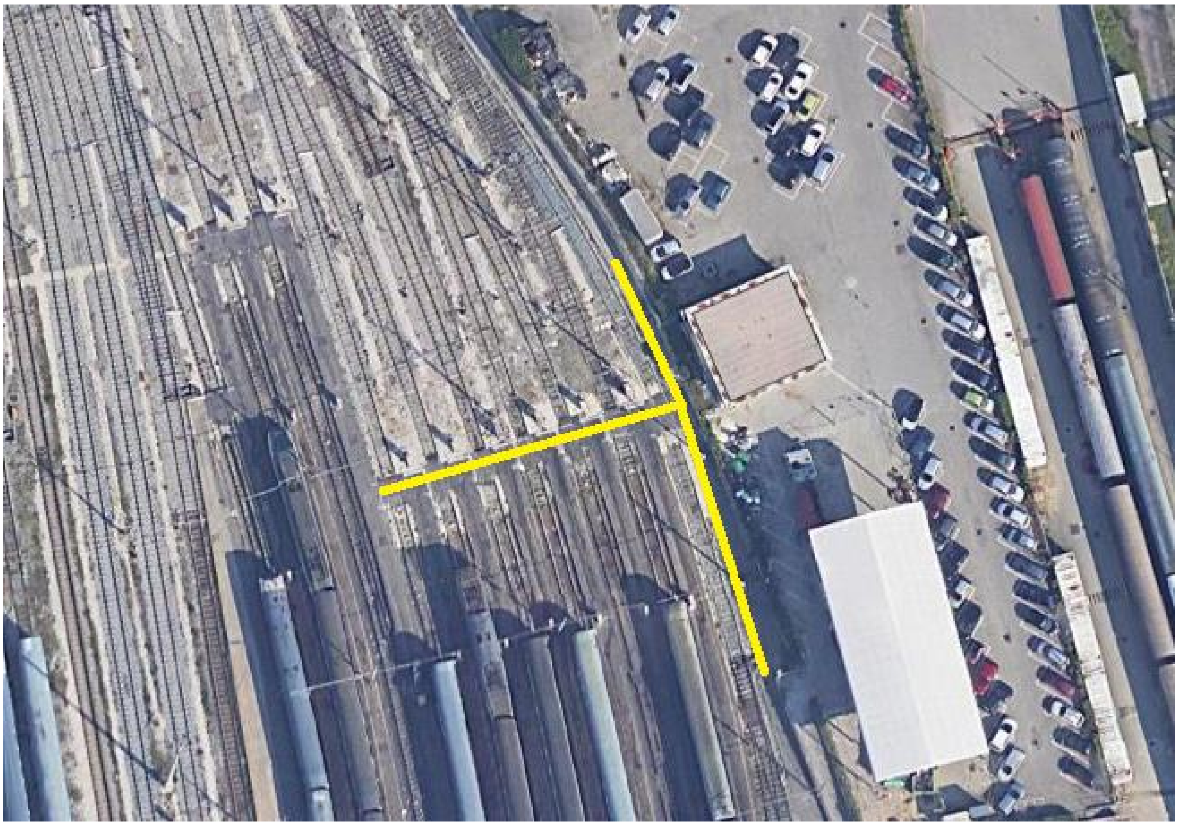

Figure 25 Position n. 2 from Google Maps

We moved from the Position 1 to the part where trains are parked. When trains are stationary at the stopover, they keep the engine running for feeding internal systems, as cooling or heating. In that specific case, Position 2 is located at the opposite part of the train's head, so the noise produced by engines is "far" from the recording location and quite low. Yellow line also in this case represent the walk done to record. Time frames are usually about 30 seconds or 1 minute or more, because we want to analyse the subjective perception with a better description of the event. By the way in this site, we chose two intervals of 1 minute duration but also other three intervals of 3 seconds just to compare the former intervals with the latter ones.

The Frame 1 represents noise captured in the part of the walk far away from the trains, always along the yellow line. Frame 2 recorded workers cleaning the cabins of the trains. Frame 3 focused on the noise generated by the machine used to sanitize the cabins.

Figure 26 Detail of Position n. 2

Coordinates	**45.50959375764549, 9.217610781420547**
Noise sources	**The main source is train's engines with a low contributions**
Buildings	**There are no occupied buildings. A car parking is present**
Number of records	**1**
Duration of records	**10 min**
Time Frame 1	**2:07 – 2:10**
Time Frame 2	**4:58 – 5:01**
Time Frame 3	**8:13 – 8:16**
Time Frame 4	**0:52 – 1:52**
Time Frame 5	**3:30 – 4:30**

3.4 Position 3

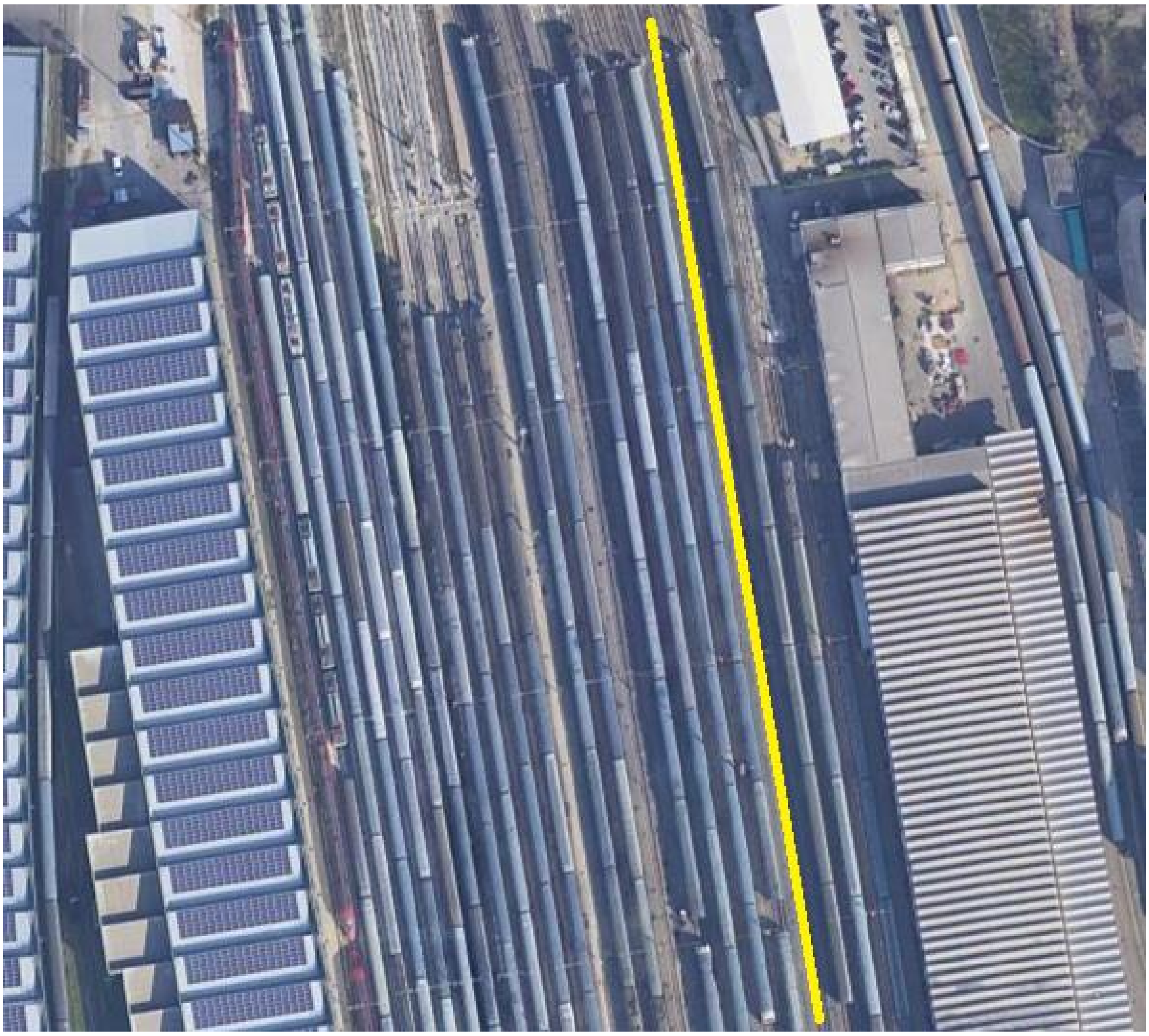

Figure 27 Position n.3 from Google Maps

Differently from the previous case, here we have done the walk between trains, moving from the train queue to those with engines, to evaluate the changing in noise perception. Now we pass along the whole train, and we can record also noise generated by internal systems.

Frame 1 and Frame 2 were selected to study psychoacoustic parameters close to the engines of the train, in the lower part of the above picture. Instead Frame 3 recorded the noise on the opposite part at the end of the trains, in the upper part of the picture.

Figure 28 Detail of Position n.3

In the walking number 3, we have a long-time interval about 3 minutes which describes the whole path close to the train: starting from the end of the train, reaching the head where there is engine, and coming back to the train queue. This period was divided into three parts, called Time Frame 4, 5 and 6 respectively. Number 5 is the part recorded close to the head of the trains, for this reason we will use the values of Time frame 4 and 6 as reference values for the “silence condition”.

Coordinates	**45.50959375764549, 9.217610781420547**
Noise sources	**There are 3 sources: internal train systems, cleaning operations, engines. In particular, engine noise grows moving to head of trains.**
Buildings	**The building near this position is used for maintenance operations**
Number of records	**1**
Duration of records	**10 min**
Time Frame 1	**1:35 – 1:38**
Time Frame 2	**2:28 – 2:31**
Time Frame 3	**6:24 – 6:27**
Time Frame 4	**0:35 – 1:35**
Time Frame 5	**1:35 – 2:35**
Time Frame 6	**2:35 – 3:35**

3.5 Position 4

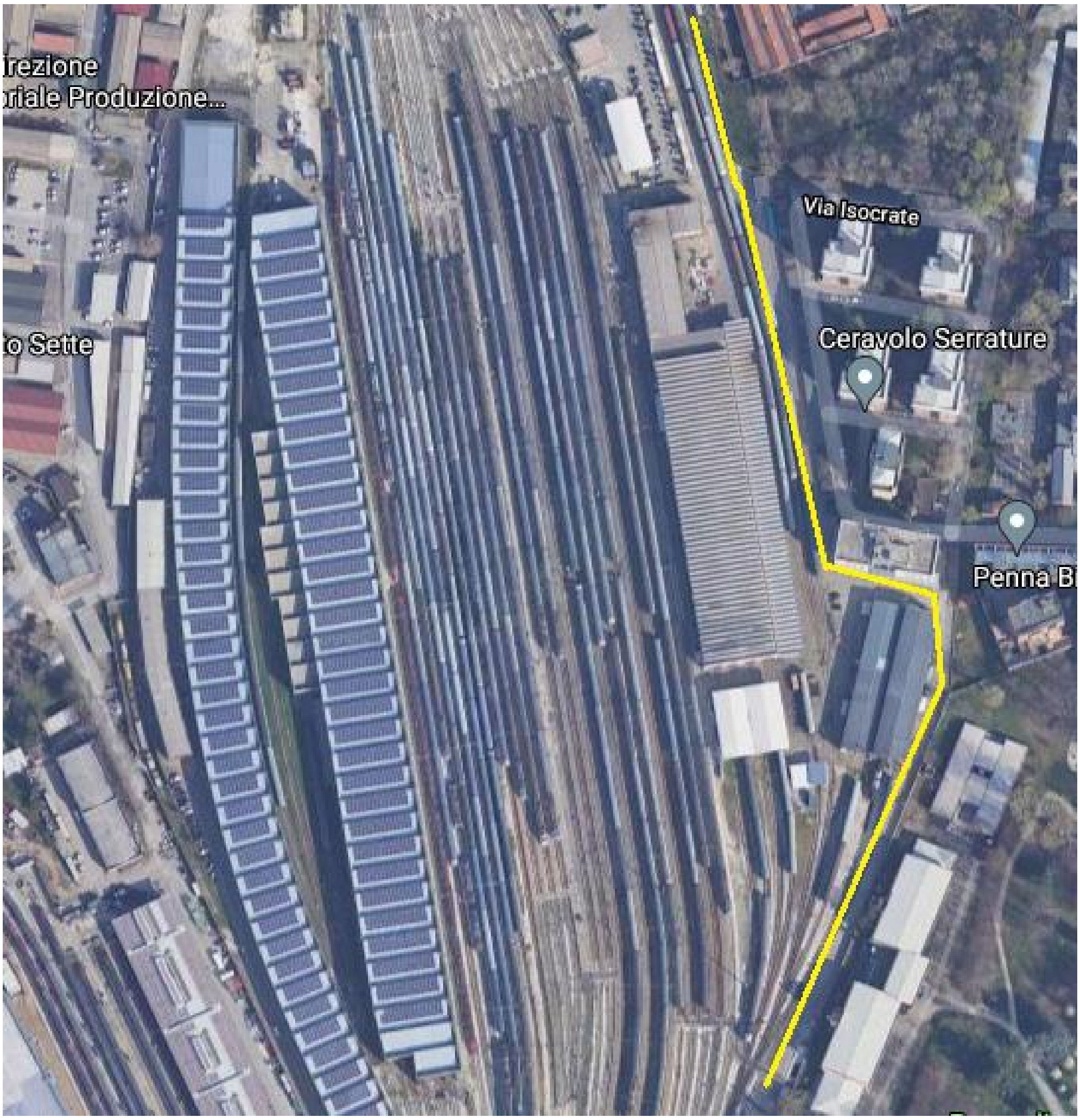

Figure 29 Position n. 4 from Google Maps

This is the last record that considers noise generated by stationary train and/or maintenance works. Yellow line represents a complete path because it includes the background noise from engines, discontinuous noise coming from maintenance and on the right side of the picture we have many kinds of building as houses, shops, a school, a library, and offices of Trenitalia at the end of the walk. All the buildings on the left of path are used for maintenance.

Frame 1 can be located before the buildings for maintenance operations and Via Socrate. Frame 2 is the time interval precisely recorded in the curve of the yellow path. Finally, we have Frame 3 which will show the noise contribution near the refrigeration system produced by Thermo King company.

Here it has been very difficult to obtain 1 consecutive minute without wind noise contribution, in fact we selected the first 28 seconds as “silence condition” which will be called Time Frame 4, then we compare these values with the worst scenario: 40 seconds close the refrigeration system Thermo King, the Time Frame 5. Another time interval has been analysed in order to have as many data as possible, from 2:37 to 3:37, named time Frame 6.

Figure 30 Detail of Position n. 4 - starting point.

Figure 31 Detail of Position n. 4

Figure 32 Detail of Position n. 4 - curve

Figure 33 Detail of Position n. 4 - refrigeration system

Coordinates	**Starting point: 45.50980052036316, 9.21825719380218** **Ending point: 45.504567309566916, 9.217988972900566**
Noise sources	**Background noise from engines, noise from maintenance work and local high contributions by refrigeration unit "Thermo King"**
Buildings	**Buildings on the right: houses, shops, school, library, offices.** **Buildings on the left: maintenance work**
Number of records	**1**
Duration of records	**10 min**
Time Frame 1	**1:54 – 1:57**
Time Frame 2	**5:00 – 5:03**
Time Frame 3	**7:51 – 7:54**
Time Frame 4	**0:00 – 0:28**
Time Frame 5	**7:50 – 8:30**
Time Frame 6	**2:37 – 3:37**

3.6 Position 5

Figure 34 Position n. 5 from Google Maps

The final site counts many records taken in different ways and focus on different kind of trains. Some records are made in a fixed position instead other by doing the typical walk. Both types of records are situated along the yellow path.

Here we have done many registrations considering the various trains which generate noise: high speed trains (FRECCIAROSSA and FRECCIARGENTO), low speed trains (REGIONALE), locomotives for train handling. The latter are diesel engine equipped. Moreover, we have recorded a FRECCIAROSSA which was leaving the stopover and two trains passing contemporary, to be precise FRECCIARGENTO and REGIONALE.

Figure 35 Detail of Position n. 5

Frame 1, 2, and 3 of Record 1 describe a quiet situation in which no trains pass and no workers around and there is only one train FRECCIAROSSA in stationary condition with engine on.

First minute of Record 1 is considered to compare its values with the ones from the shortest time intervals.

On Record 2 we consider the noise contribution of two kinds of train, FRECCIARGENTO (high speed train) and REGIONALE (low speed train). In Frame 1 FRECCIARGENTO is leaving the stopover and in Frame 2 that train passes close to the yellow path. The same study was done in Frame 3 and Frame 4 but the train considered is REGIONALE, which has a diesel locomotive. Here the comparison is made for the train FRECCIARGENTO, precisely with two intervals, from 1:30 to 2:30 valuating the coming of the train and from 2:30 to 3:00 when train passes as in Frame 2.

On record 3 only a diesel locomotive is considered. The latter is different from train REGIONALE because we deal with a single locomotive, used to manage wagons within the stopover. Frame 1 analyses the arrival of this locomotive, during the Frame 2 it is passing close to the recording point, the Frame 3 recorded locomotive that is moving away. Since this record does not reach 1 minute, the comparison has made analysing the whole duration of 46 seconds.

In this site of recording, we can also investigate the contribution of squeal noise. Due to low speed its component is not so relevant for the soundscape, anyway, squeal noise is included on Frame 3 of Record 2 and Frame 2 of Record 3.

Figure 36 Detail of Position n. 5

Coordinates	**45.50340180127974, 9.217704658740777**
Noise sources	**Diesel engines, high speed trains engines, friction between rail and wheels (squeal noise)**
Buildings	**Houses and offices.**
Number of records	**3**
Duration of record 1	**5:06**
Duration of record 2	**5:09**
Duration of record 3	**0:46**
Record 1, Time Frame 1	**0:26 – 0:29**
Record 1, Time Frame 2	**1:04 – 1:07**
Record 1, Time Frame 3	**4:34 – 4:37**
Record 1, Time Frame 4	**0:00 – 1:00**
Record 2, Time Frame 1	**2:00 – 2:03**
Record 2, Time Frame 2	**2:38 – 2:41**
Record 2, Time Frame 3	**3:58 – 4:01**
Record 2, Time Frame 4	**4:34 – 4:37**
Record 2, Time Frame 5	**1:30 – 2:30**
Record 2, Time Frame 6	**2:30 – 3:00**
Record 3, Time Frame 1	**0:07 – 0:10**
Record 3, Time Frame 2	**0:14 – 0:17**
Record 3, Time Frame 3	**0:23 – 0:26**
Record 3, Time Frame 4	**0:00 – 0:46**

4. Results from analysis

The analysis of psychoacoustic parameters starts loading all recording files into the software LMS Test Lab, which is strictly connected with Siemens device used to make the registration. Once files have been uploaded, we select the record we want to analyse, we select the parameters to be extracted and finally software processes data and shows us values.

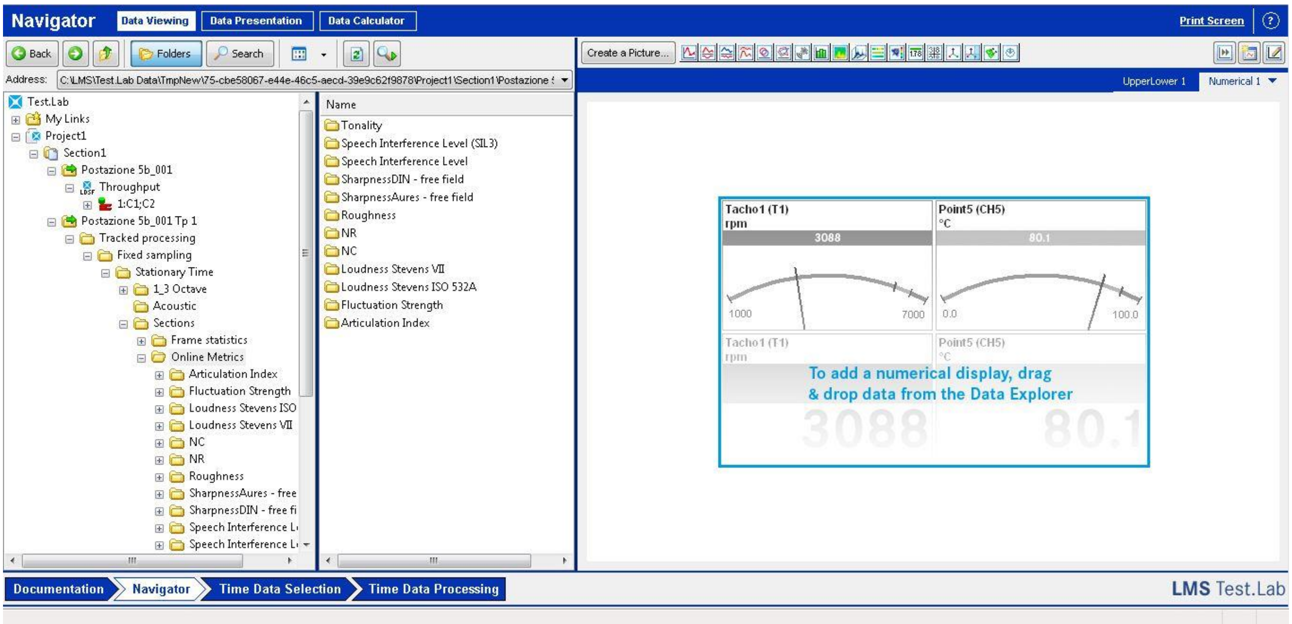

Figure 37 Selection of the record to be analysed.

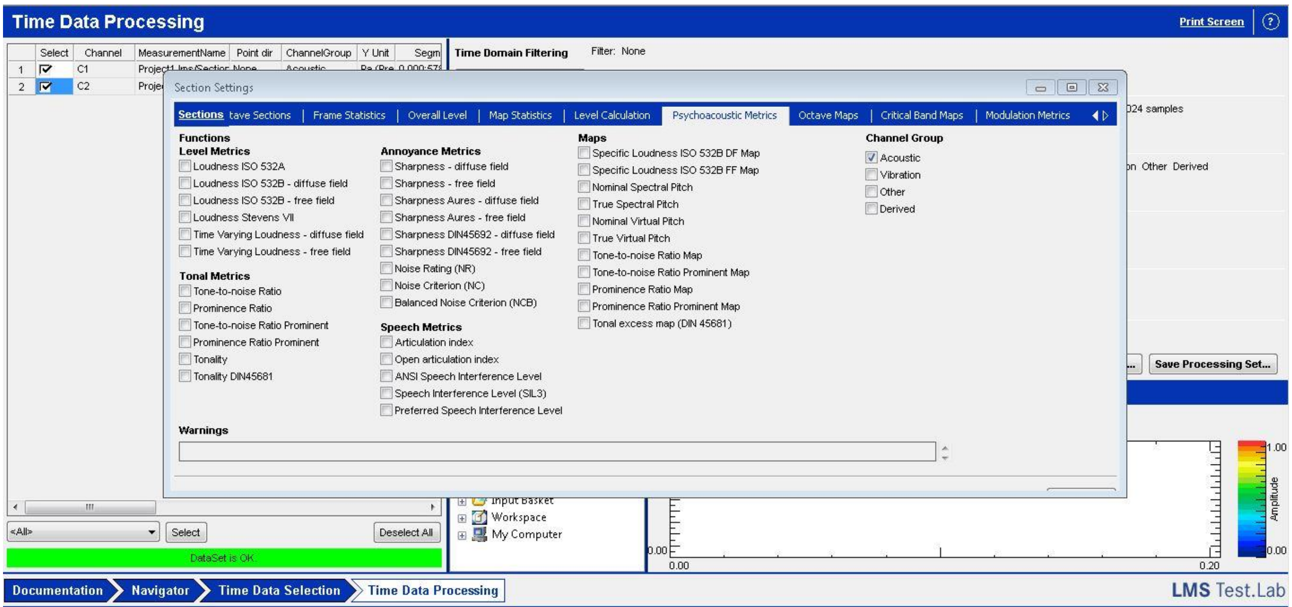

Figure 38 Selection of the parameters.

The binaural headphones have two microphones precisely located on the ears, one microphone to the right and on to the left. For this reason, all the values will be shown for both channels (named C1 and C2). Moreover, for all parameter in each frame we have considered: maximum value, minimum value, RMS (root mean square) and mean value.

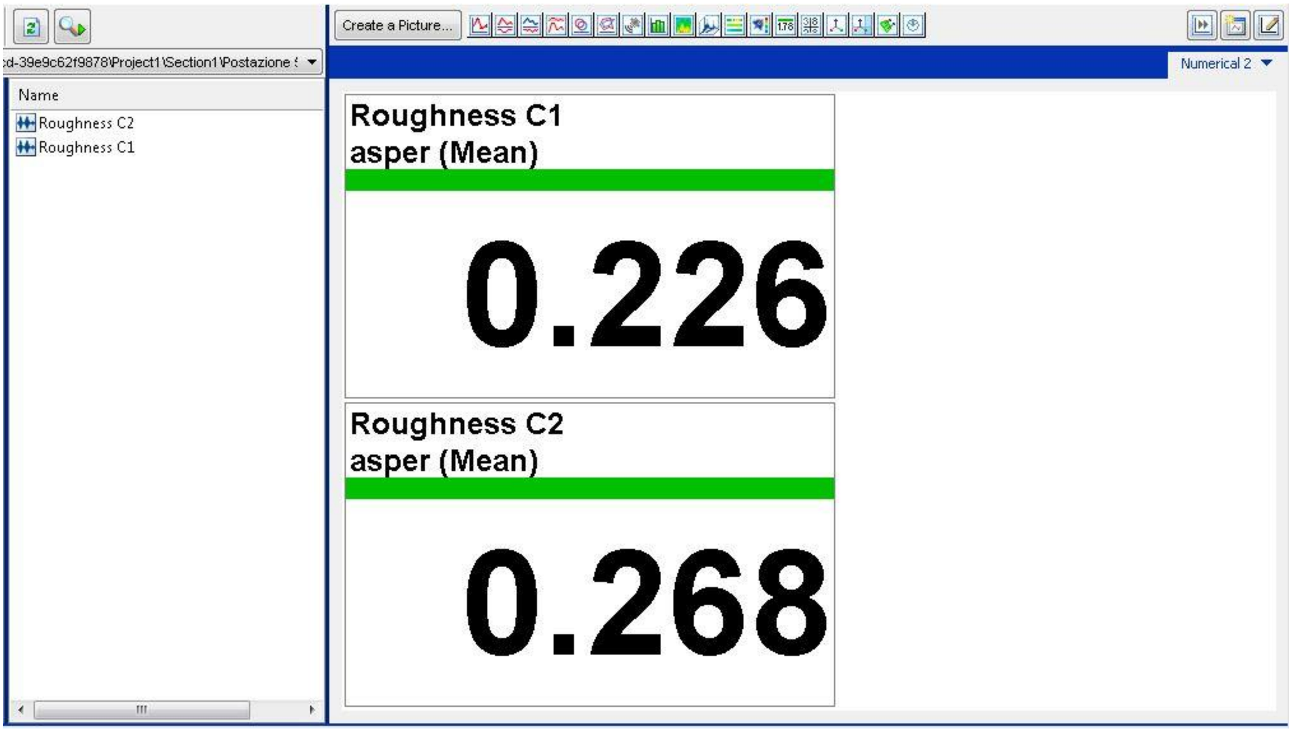

Figure 39 Example: Result of the analysis

All results have been shown in the following.

4.1 Position 1

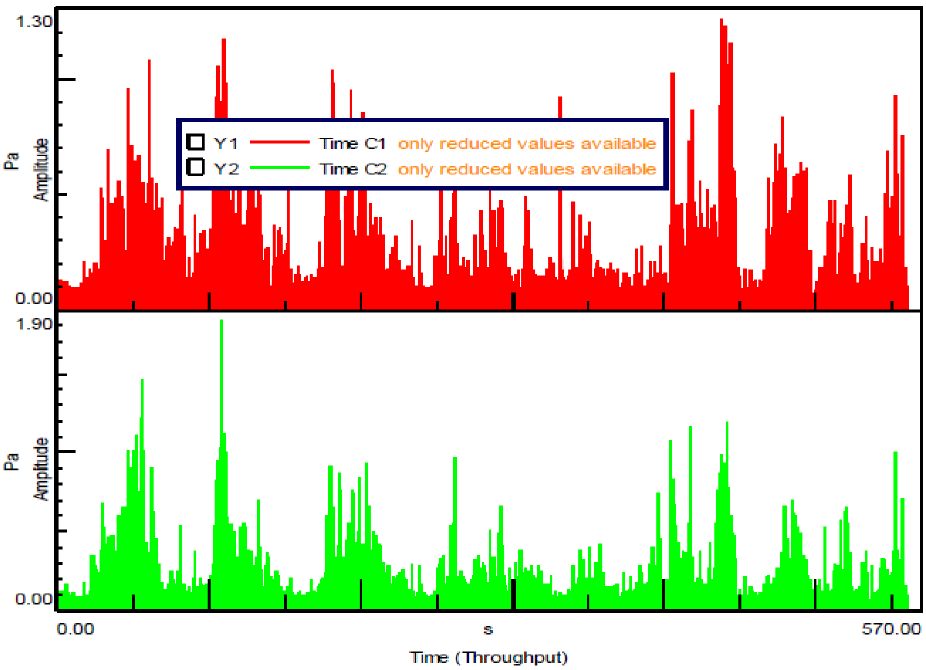

Figure 40 Position 1 - Channel 1 and Channel 2

Position 1 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,341	17,999	0	0,613
SHARPNESS DIN 45692	*acum*	1,238	1,277	1,127	1,556
ROUGHNESS	*asper*	0,0403	0,63	0,167	1,211
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,304	1,313	1,227	1,371
C2					
LOUDNESS ISO 532 B	*sone*	0,297	16,052	0	0,588
SHARPNESS DIN 45692	*acum*	1,16	1,164	1,018	1,296
ROUGHNESS	*asper*	0,4	0,683	0,126	1,336
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,408	1,42	1,261	1,495

Position 1 – Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,332	17,502	0	0,561
SHARPNESS DIN 45692	*acum*	1,251	1,272	1,123	1,411
ROUGHNESS	*asper*	0,757	0,955	0,198	1,479
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,524	1,542	1,342	1,681
C2					
LOUDNESS ISO 532 B	*sone*	0,305	16,297	0	0,541
SHARPNESS DIN 45692	*acum*	1,193	1,202	1,068	1,28
ROUGHNESS	*asper*	0,597	0,794	0,173	1,099
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,541	1,565	1,417	1,662

Position 1 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,269	15,112	0	0,511
SHARPNESS DIN 45692	*acum*	1,068	1,058	1,021	1,117
ROUGHNESS	*asper*	0,257	0,256	0,161	0,493
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,304	1,301	1,113	1,484
C2					
LOUDNESS ISO 532 B	*sone*	0,266	14,939	0	0,517
SHARPNESS DIN 45692	*acum*	1,06	1,043	0,968	1,16
ROUGHNESS	*asper*	0,259	0,261	0,148	0,558
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,311	1,321	1,182	1,489

4.2 Position 2

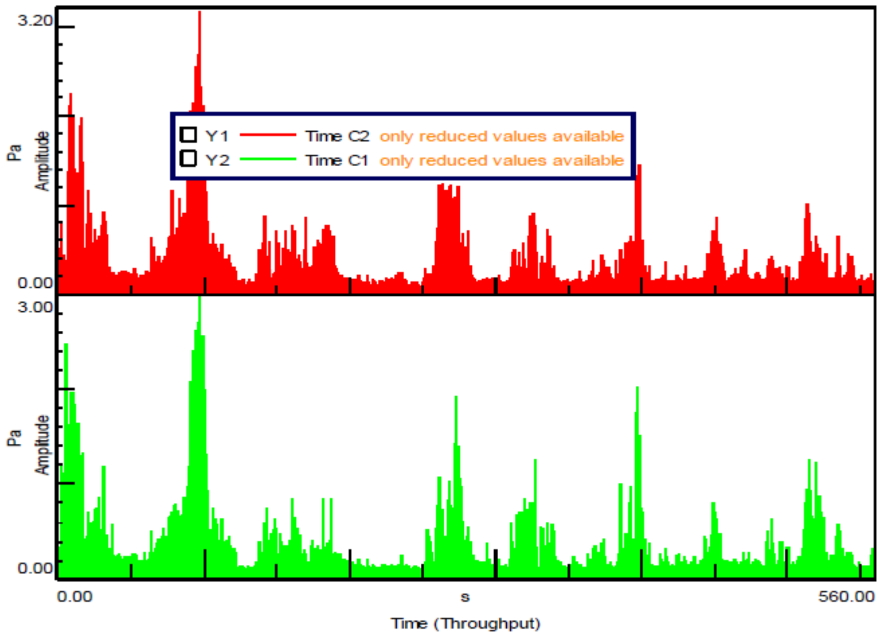

Figure 41 Position 2 - Channel 1 and Channel 2

Position 2 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,363	19,668	0	0,822
SHARPNESS DIN 45692	*acum*	1,25	1,24	1,183	1,373
ROUGHNESS	*asper*	0,388	0,382	0,148	0,734
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,233	1,2	1,098	1,42
C2					
LOUDNESS ISO 532 B	*sone*	0,337	18,468	0	0,806
SHARPNESS DIN 45692	*acum*	1,179	1,165	1,121	1,32
ROUGHNESS	*asper*	0,466	0,473	0,154	0,97
TONALITY		0,005	0,006	0	0,016
FLUCTUATION STRENGTH	*vacil*	1,248	1,212	1,112	1,539

Position 2 – Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,447	25,255	0	1,217
SHARPNESS DIN 45692	*acum*	1,165	1,171	1,098	1,281
ROUGHNESS	*asper*	0,158	0,169	0,13	0,227
TONALITY		0,014	0,021	0	0,04
FLUCTUATION STRENGTH	*vacil*	1,159	1,161	1,135	1,183
C2					
LOUDNESS ISO 532 B	*sone*	0,428	24,902	0	1,334
SHARPNESS DIN 45692	*acum*	1,151	1,152	1,098	1,221
ROUGHNESS	*asper*	0,214	0,218	0,14	0,305
TONALITY		0,006	0,01	0	0,028
FLUCTUATION STRENGTH	*vacil*	1,191	1,195	1,161	1,246

Position 2 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,481	25,902	0	0,882
SHARPNESS DIN 45692	*acum*	1,194	1,183	1,08	1,288
ROUGHNESS	*asper*	0,175	0,169	0,125	0,225
TONALITY		0,012	0,019	0	0,028
FLUCTUATION STRENGTH	*vacil*	1,109	1,125	1,047	1,24
C2					
LOUDNESS ISO 532 B	*sone*	0,604	31,113	0	0,884
SHARPNESS DIN 45692	*acum*	1,403	1,368	1,244	1,58
ROUGHNESS	*asper*	0,14	0,139	0,122	0,158
TONALITY		0,004	0,007	0	0,013
FLUCTUATION STRENGTH	*vacil*	1,079	1,092	0,976	1,189

Position 2 – Time Frame 4

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,565	90,547	0	4,989
SHARPNESS DIN 45692	*acum*	1,172	1,181	0,841	1,629
ROUGHNESS	*asper*	0,272	0,317	0,138	1,215
TONALITY		0,002	0,007	0	0,037
FLUCTUATION STRENGTH	*vacil*	1,254	1,262	0,853	1,547
C2					
LOUDNESS ISO 532 B	*sone*	1,546	88,853	0	4,842
SHARPNESS DIN 45692	*acum*	1,151	1,161	0,864	1,562
ROUGHNESS	*asper*	0,266	0,3	0,127	0,786
TONALITY		0,001	0,005	0	0,027
FLUCTUATION STRENGTH	*vacil*	1,226	1,234	0,922	1,551

Position 2 – Time Frame 5

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,54	33,056	0	1,502
SHARPNESS DIN 45692	*acum*	1,133	1,139	0,742	1,468
ROUGHNESS	*asper*	0,234	0,296	0,115	1,173
TONALITY		0,032	0,048	0	0,145
FLUCTUATION STRENGTH	*vacil*	1,303	1,317	1,052	1,893
C2					
LOUDNESS ISO 532 B	*sone*	0,557	35,336	0	1,75
SHARPNESS DIN 45692	*acum*	1,084	1,097	0,716	1,517
ROUGHNESS	*asper*	0,256	0,337	0,109	1,196
TONALITY		0,042	0,062	0	0,162
FLUCTUATION STRENGTH	*vacil*	1,283	1,294	1,041	1,931

4.3 Position 3

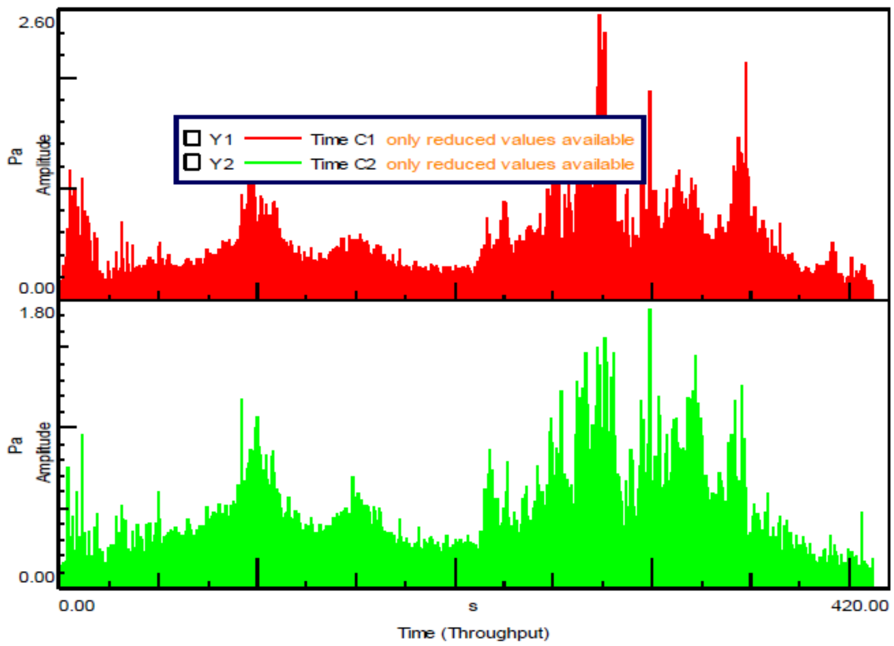

Figure 42 Position 3 - Channel 1 and Channel 2

Position 3 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,999	106,91	0	3,86
SHARPNESS DIN 45692	*acum*	1,322	1,323	1,316	1,33
ROUGHNESS	*asper*	0,274	0,279	0,219	0,327
TONALITY		0,055	0,066	0	3,86
FLUCTUATION STRENGTH	*vacil*	1,117	1,114	1,087	1,115
C2					
LOUDNESS ISO 532 B	*sone*	1,558	84,845	0	2,622
SHARPNESS DIN 45692	*acum*	1,223	1,221	1,215	1,235
ROUGHNESS	*asper*	0,249	0,249	0,204	0,314
TONALITY		0,03	0,038	0	0,063
FLUCTUATION STRENGTH	*vacil*	1,08	1,082	1,061	1,098

Position 3 - Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,201	64,789	0	2,385
SHARPNESS DIN 45692	*acum*	1,304	1,299	1,26	1,33
ROUGHNESS	*asper*	0,243	0,236	0,198	0,294
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,055	1,053	1,021	1,108
C2					
LOUDNESS ISO 532 B	*sone*	1,223	64,687	0	2,039
SHARPNESS DIN 45692	*acum*	1,384	1,383	1,349	1,423
ROUGHNESS	*asper*	0,242	0,245	0,202	0,306
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,172	1,182	1,065	1,203

Position 3 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,628	34,132	0	1,222
SHARPNESS DIN 45692	*acum*	1,254	1,254	1,192	1,319
ROUGHNESS	*asper*	0,182	0,18	0,136	0,222
TONALITY		0,002	0,003	0	0,008
FLUCTUATION STRENGTH	*vacil*	1,175	1,182	1,123	1,208
C2					
LOUDNESS ISO 532 B	*sone*	0,522	28,584	0	1,009
SHARPNESS DIN 45692	*acum*	1,198	1,2	1,189	1,21
ROUGHNESS	*asper*	0,18	0,182	0,165	0,191
TONALITY		0,005	0,009	0	0,027
FLUCTUATION STRENGTH	*vacil*	1,111	1,118	1,048	1,165

Position 3 – Time Frame 4

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,977	52,966	0	1,78
SHARPNESS DIN 45692	*acum*	1,198	1,198	1,121	1,334
ROUGHNESS	*asper*	0,209	0,213	0,148	0,334
TONALITY		0,012	0,026	0	0,179
FLUCTUATION STRENGTH	*vacil*	1,129	1,13	1,028	1,352
C2					
LOUDNESS ISO 532 B	*sone*	1,095	58,207	0	1,817
SHARPNESS DIN 45692	*acum*	1,323	1,325	1,137	1,418
ROUGHNESS	*asper*	0,219	0,221	0,135	0,294
TONALITY		0,015	0,03	0	0,205
FLUCTUATION STRENGTH	*vacil*	1,105	1,106	0,973	1,425

Position 3 – Time Frame 5

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,251	67,144	0	2,255
SHARPNESS DIN 45692	*acum*	1,294	1,294	1,185	1,398
ROUGHNESS	*asper*	0,229	0,233	0,152	0,352
TONALITY		0,011	0,021	0	0,084
FLUCTUATION STRENGTH	*vacil*	1,115	1,116	0,983	1,236
C2					
LOUDNESS ISO 532 B	*sone*	1,166	62,513	0	2,126
SHARPNESS DIN 45692	*acum*	1,317	1,319	1,182	1,474
ROUGHNESS	*asper*	0,225	0,227	0,15	0,326
TONALITY		0,013	0,022	0	0,08
FLUCTUATION STRENGTH	*vacil*	1,138	1,14	0,972	1,292

Position 3 – Time Frame 6

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,783	41,475	0	1,524
SHARPNESS DIN 45692	*acum*	1,403	1,405	1,245	1,531
ROUGHNESS	*asper*	0,18	0,185	0,111	0,423
TONALITY		0,032	0,047	0	0,143
FLUCTUATION STRENGTH	*vacil*	1,109	1,111	0,987	1,269
C2					
LOUDNESS ISO 532 B	*sone*	0,826	43,338	0	1,492
SHARPNESS DIN 45692	*acum*	1,451	1,452	1,319	1,592
ROUGHNESS	*asper*	0,184	0,187	0,123	0,378
TONALITY		0,031	0,046	0	0,129
FLUCTUATION STRENGTH	*vacil*	1,091	1,094	0,881	1,243

4.4 Position 4

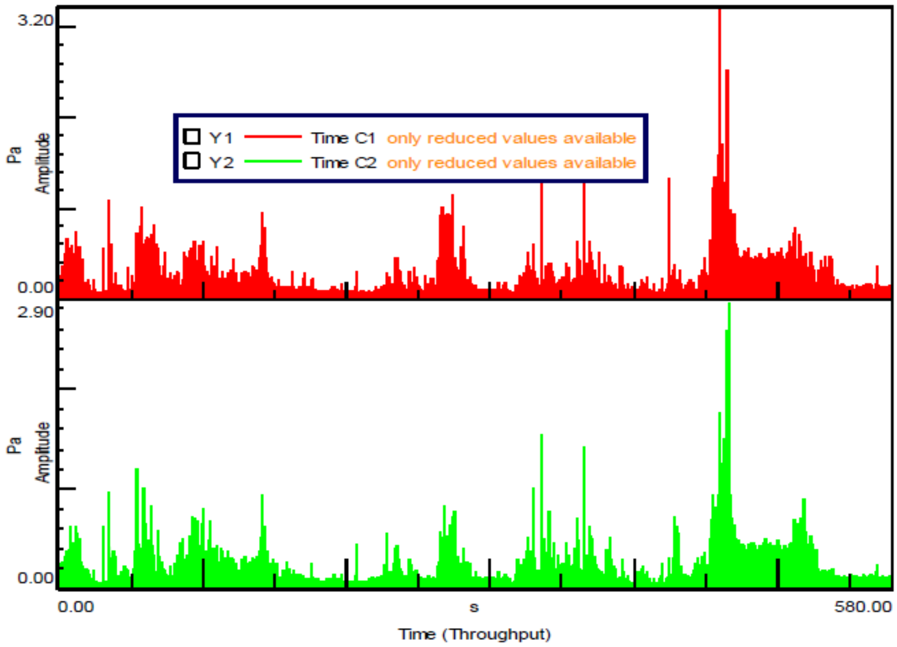

Figure 43 Position 4 - Channel 1 and Channel 2

Position 4 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,259	14,014	0	0,48
SHARPNESS DIN 45692	*acum*	1,25	1,264	1,124	1,329
ROUGHNESS	*asper*	0,219	0,221	0,185	0,237
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,384	1,379	1,28	1,551
C2					
LOUDNESS ISO 532 B	*sone*	0,313	18,744	0	1,036
SHARPNESS DIN 45692	*acum*	1,148	1,195	0,955	1,413
ROUGHNESS	*asper*	0,39	0,412	0,158	0,607
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,622	1,618	1,537	1,723

Position 4 – Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,263	14,376	0	0,529
SHARPNESS DIN 45692	*acum*	1,157	1,159	1,114	1,22
ROUGHNESS	*asper*	0,15	0,155	0,127	0,174
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,169	1,179	1,108	1,215
C2					
LOUDNESS ISO 532 B	*sone*	0,254	13,831	0	0,472
SHARPNESS DIN 45692	*acum*	1,157	1,152	1,009	1,307
ROUGHNESS	*asper*	0,169	0,169	0,11	0,296
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,183	1,195	1,069	1,305

Position 4 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,195	63,949	0	2,497
SHARPNESS DIN 45692	*acum*	1,339	1,337	1,322	1,363
ROUGHNESS	*asper*	0,231	0,243	0,17	0,292
TONALITY		0,002	0,006	0	0,012
FLUCTUATION STRENGTH	*vacil*	1,111	1,117	1,077	1,148
C2					
LOUDNESS ISO 532 B	*sone*	1,088	59,336	0	2,625
SHARPNESS DIN 45692	*acum*	1,273	1,272	1,259	1,291
ROUGHNESS	*asper*	0,205	0,21	0,169	0,246
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,065	1,064	1,042	1,082

Position 4 – Time Frame 4

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,512	31,332	0	1,553
SHARPNESS DIN 45692	*acum*	1,094	1,104	0,801	1,34
ROUGHNESS	*asper*	0,301	0,446	0,107	2,138
TONALITY		0,006	0,016	0	0,088
FLUCTUATION STRENGTH	*vacil*	1,377	1,399	1,091	1,992
C2					
LOUDNESS ISO 532 B	*sone*	0,481	27,171	0	1,187
SHARPNESS DIN 45692	*acum*	1,211	1,222	0,828	1,483
ROUGHNESS	*asper*	0,284	0,393	0,1	1,638
TONALITY		0,004	0,012	0	0,049
FLUCTUATION STRENGTH	*vacil*	1,384	1,402	1,094	1,92

Position 4 – Time Frame 5

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,14	60,519	0	2,281
SHARPNESS DIN 45692	*acum*	1,359	1,36	1,179	1,436
ROUGHNESS	*asper*	0,232	0,234	0,158	0,315
TONALITY		0	0,002	0	0,018
FLUCTUATION STRENGTH	*vacil*	1,092	1,093	0,969	1,0275
C2					
LOUDNESS ISO 532 B	*sone*	1,011	54,754	0	2,266
SHARPNESS DIN 45692	*acum*	1,276	1,278	1,106	1,336
ROUGHNESS	*asper*	0,22	0,221	0,163	0,289
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,115	1,117	1,017	1,263

Position 4 – Time Frame 6

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,317	18,678	0	0,86
SHARPNESS DIN 45692	*acum*	1,025	1,029	0,81	1,35
ROUGHNESS	*asper*	0,168	0,189	0,9	0,658
TONALITY		0,015	0,025	0	0,1
FLUCTUATION STRENGTH	*vacil*	1,191	1,196	0,989	1,49
C2					
LOUDNESS ISO 532 B	*sone*	0,342	19,867	0	0,905
SHARPNESS DIN 45692	*acum*	1,073	1,076	0,862	1,476
ROUGHNESS	*asper*	0,21	0,254	0,092	0,956
TONALITY		0,011	0,019	0	0,072
FLUCTUATION STRENGTH	*vacil*	1,241	1,247	1,016	1,568

4.5 Position 5

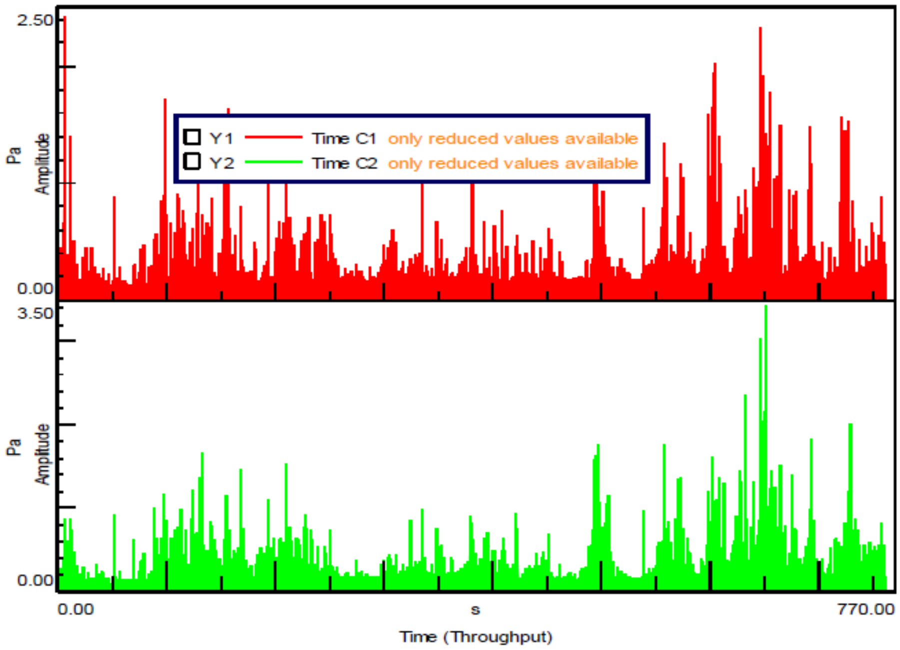

Figure 44 Position 5 - Record 1 - Channel 1 and Channel 2

Position 5 – Record 1 – Time Frame 1

C1	unit measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,537	28,546	0	0,932
SHARPNESS DIN 45692	*acum*	1,257	1,259	1,124	1,397
ROUGHNESS	*asper*	0,23	0,263	0,136	0,929
TONALITY		0,005	0,011	0	0,045
FLUCTUATION STRENGTH	*vacil*	1,237	1,244	1,005	1,606
C2					
LOUDNESS ISO 532 B	*sone*	0,511	27,088	0	0,856
SHARPNESS DIN 45692	*acum*	1,202	1,206	0,991	1,454
ROUGHNESS	*asper*	0,236	0,271	0,142	0,798
TONALITY		0,002	0,006	0	0,026
FLUCTUATION STRENGTH	*vacil*	1,246	1,254	0,977	1,523

Position 5 – Record 1 – Time Frame 2

C1	unit measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,715	37,577	0	1,264
SHARPNESS DIN 45692	*acum*	1,361	1,364	1,338	1,372
ROUGHNESS	*asper*	0,215	0,214	0,155	0,31
TONALITY		0,013	0,014	0	0,021
FLUCTUATION STRENGTH	*vacil*	1,169	1,171	1,14	1,217
C2					
LOUDNESS ISO 532 B	*sone*	0,79	40,913	0	1,204
SHARPNESS DIN 45692	*acum*	1,439	1,437	1,4	1,492
ROUGHNESS	*asper*	0,201	0,205	0,163	0,225
TONALITY		0,014	0,017	0	0,029
FLUCTUATION STRENGTH	*vacil*	1,013	1,021	0,975	1,063

Position 5 – Record 1 – Time Frame 3

C1	unit measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,564	30,237	0	1,217
SHARPNESS DIN 45692	*acum*	1,205	1,198	1,169	1,283
ROUGHNESS	*asper*	0,309	0,391	0,175	0,629
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,13	1,123	1,096	1,188
C2					
LOUDNESS ISO 532 B	*sone*	0,539	29,268	0	1,217
SHARPNESS DIN 45692	*acum*	1,203	1,205	1,15	1,271
ROUGHNESS	*asper*	0,265	0,322	0,151	0,54
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,205	1,212	1,105	1,278

Position 5 – Record 1 – Time Frame 4

C1	unit measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,536	28,572	0	0,953
SHARPNESS DIN 45692	*acum*	1,232	1,235	0,89	1,463
ROUGHNESS	*asper*	0,263	0,315	0,136	1,065
TONALITY		0,004	0,01	0	0,045
FLUCTUATION STRENGTH	*vacil*	1,3	1,311	0,988	1,898
C2					
LOUDNESS ISO 532 B	*sone*	0,521	27,597	0	0,874
SHARPNESS DIN 45692	*acum*	1,222	1,226	0,991	1,651
ROUGHNESS	*asper*	0,295	0,357	0,142	1,162
TONALITY		0,002	0,009	0	0,055
FLUCTUATION STRENGTH	*vacil*	1,306	1,317	0,982	1,687

Position 5 – Record 2 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,782	42,529	0	1,881
SHARPNESS DIN 45692	*acum*	1,405	1,401	1,375	1,443
ROUGHNESS	*asper*	0,201	0,207	0,158	0,236
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,121	1,116	1,059	1,177
C2					
LOUDNESS ISO 532 B	*sone*	0,683	37,62	0	1,648
SHARPNESS DIN 45692	*acum*	1,262	1,254	1,223	1,305
ROUGHNESS	*asper*	0,187	0,19	0,167	0,206
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,098	1,096	1,061	1,151

Position 5 – Record 2 – Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,43	78,699	0	3,098
SHARPNESS DIN 45692	*acum*	1,207	1,217	1,121	1,257
ROUGHNESS	*asper*	0,262	0,262	0,204	0,303
TONALITY		0,006	0,011	0	0,031
FLUCTUATION STRENGTH	*vacil*	1,11	1,105	1,091	1,131
C2					
LOUDNESS ISO 532 B	*sone*	1,535	83,299	0	3,089
SHARPNESS DIN 45692	*acum*	1,26	1,264	1,233	1,279
ROUGHNESS	*asper*	0,264	0,264	0,246	0,284
TONALITY		0,005	0,012	0	0,024
FLUCTUATION STRENGTH	*vacil*	1,169	1,172	1,144	1,182

Position 5 – Record 2 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,586	31,537	10,397	11,276
SHARPNESS DIN 45692	*acum*	1,278	1,265	1,199	1,355
ROUGHNESS	*asper*	0,187	0,188	0,175	0,199
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,142	1,134	1,094	1,19
C2					
LOUDNESS ISO 532 B	*sone*	0,65	34,381	0	1,248
SHARPNESS DIN 45692	*acum*	1,425	1,424	1,34	1,522
ROUGHNESS	*asper*	0,208	0,211	0,191	0,237
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,28	1,283	1,248	1,32

Position 5 – Record 2 – Time Frame 4

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,846	45,038	0	1,575
SHARPNESS DIN 45692	*acum*	1,306	1,315	1,188	1,368
ROUGHNESS	*asper*	0,255	0,263	0,212	0,304
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,194	1,206	1,074	1,228
C2					
LOUDNESS ISO 532 B	*sone*	0,753	40,935	0	1,552
SHARPNESS DIN 45692	*acum*	1,192	1,202	1,079	1,358
ROUGHNESS	*asper*	0,234	0,24	0,193	0,297
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,242	1,247	1,196	1,282

Position 5 – Record 2 – Time Frame 5

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,748	39,761	0	1,509
SHARPNESS DIN 45692	*acum*	1,394	1,404	1,084	1,736
ROUGHNESS	*asper*	0,227	0,248	0,148	1,049
TONALITY		0,009	0,024	0	0,135
FLUCTUATION STRENGTH	*vacil*	1,238	1,245	1,062	1,877
C2					
LOUDNESS ISO 532 B	*sone*	0,714	38,245	0	1,457
SHARPNESS DIN 45692	*acum*	1,304	1,306	1,117	1,499
ROUGHNESS	*asper*	0,225	0,262	0,124	1,204
TONALITY		0,012	0,032	0	0,173
FLUCTUATION STRENGTH	*vacil*	1,217	1,221	1,031	1,481

Position 5 – Record 2 – Time Frame 6

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,098	60,205	0	2,363
SHARPNESS DIN 45692	*acum*	1,183	1,186	1,042	1,4
ROUGHNESS	*asper*	0,225	0,24	0,143	0,645
TONALITY		0,016	0,024	0	0,066
FLUCTUATION STRENGTH	*vacil*	1,16	1,16	1,051	1,505
C2					
LOUDNESS ISO 532 B	*sone*	1,141	62,222	0	2,329
SHARPNESS DIN 45692	*acum*	1,178	1,18	1,052	1,31
ROUGHNESS	*asper*	0,227	0,263	0,144	1,156
TONALITY		0,023	0,032	0	0,094
FLUCTUATION STRENGTH	*vacil*	1,153	1,154	1,029	1,428

Position 5 – Record 3 – Time Frame 1

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,201	69,621	0	3,921
SHARPNESS DIN 45692	*acum*	1,248	1,228	1,034	1,481
ROUGHNESS	*asper*	0,285	0,283	0,264	0,298
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,204	1,198	1,181	1,249
C2					
LOUDNESS ISO 532 B	*sone*	1,213	69,842	0	3,882
SHARPNESS DIN 45692	*acum*	1,233	1,226	0,086	1,366
ROUGHNESS	*asper*	0,285	0,289	0,233	0,354
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,238	1,226	1,16	1,332

Position 5 – Record 3 – Time Frame 2

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	1,237	66,57	0	2,751
SHARPNESS DIN 45692	*acum*	1,344	1,355	1,256	1,397
ROUGHNESS	*asper*	0,256	0,253	0,24	0,3
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,366	1,365	1,337	1,391
C2					
LOUDNESS ISO 532 B	*sone*	1,063	58,629	0	2,646
SHARPNESS DIN 45692	*acum*	1,255	1,266	1,19	1,358
ROUGHNESS	*asper*	0,25	0,22	0,199	0,258
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,262	1,26	1,224	1,293

Position 5 – Record 3 – Time Frame 3

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,61	34,943	0	1,962
SHARPNESS DIN 45692	*acum*	1,193	1,194	1,078	1,305
ROUGHNESS	*asper*	0,204	0,2	0,165	0,263
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,177	1,176	1,101	1,268
C2					
LOUDNESS ISO 532 B	*sone*	0,553	33,01	0	1,977
SHARPNESS DIN 45692	*acum*	1,067	1,067	0,965	1,195
ROUGHNESS	*asper*	0,186	0,18	0,144	0,238
TONALITY		0	0	0	0
FLUCTUATION STRENGTH	*vacil*	1,236	1,234	1,15	1,354

Position 5 – Record 3 – Time Frame 4

C1	Unit Measure	Mean value	RMS	Min value	Max value
LOUDNESS ISO 532 B	*sone*	0,931	50,779	0	2,394
SHARPNESS DIN 45692	*acum*	1,198	1,206	0,95	1,481
ROUGHNESS	*asper*	0,216	0,224	0,103	0,399
TONALITY		0,002	0,009	0	0,05
FLUCTUATION STRENGTH	*vacil*	1,224	1,231	0,96	1,542
C2					
LOUDNESS ISO 532 B	*sone*	0,854	47,579	0	2,378
SHARPNESS DIN 45692	*acum*	1,136	1,144	0,901	1,567
ROUGHNESS	*asper*	0,213	0,221	0,094	0,36
TONALITY		0,001	0,005	0	0,032
FLUCTUATION STRENGTH	*vacil*	1,195	1,203	0,832	1,545

5. Resume data and conclusions

The following diagrams show how a single parameter varies among the Positions. We have to state that Position 1 can represent the reference value for P2, P3 and P4, while P5 (r1) could be the reference record for P5 (r2) and P5 (r3). This can be true because in P5 (r1) there is train FRECCIAROSSA in stationary condition, which is a typical situation in a stopover, may be the best condition because there are usually more trains attending the next run. (r1, r2 and r3 are respectively Record 1, Record 2 and Record 3)

We consider Max values and RMS values the most important to investigate noise annoyance. Max value is simply the maximum value we can find in each record. As mentioned before, noise annoyance depends also on the duration of the signal and for that it should be interesting to investigate RMS (root mean square), which takes into accounts all the values in the time interval analysed.

Max values and Rms values are calculated as the average between records within each Position. Moreover, standard deviation for Max values has been calculated (in the diagrams indicated as “SD”).

In scientific journals, values are usually shown dividing the right channel and the left one, so we apply the same method in this project, which could be useful for future works. In fact, for a more accurate investigation, a questionnaire could be joined to binaural recordings. Looking at the past studies related to the noise annoyance, we can observe that most of the time questionnaire are more frequently used than binaural recordings.

For the following comparisons we can consider the records done in P1 as the reference value for P2, P3 and P4 because the environment including such position has the same characteristics, stationary trains, buildings for maintenance operations and workers on the railway, while P1 is the point farther from the sources of noise. On the other hand, P5 (r1) could be considered the reference for the whole Position 5 because there is only one train in a stationary condition, when there are usually more.

Black segments within the diagrams represent the standard deviation.

5.1 Loudness values

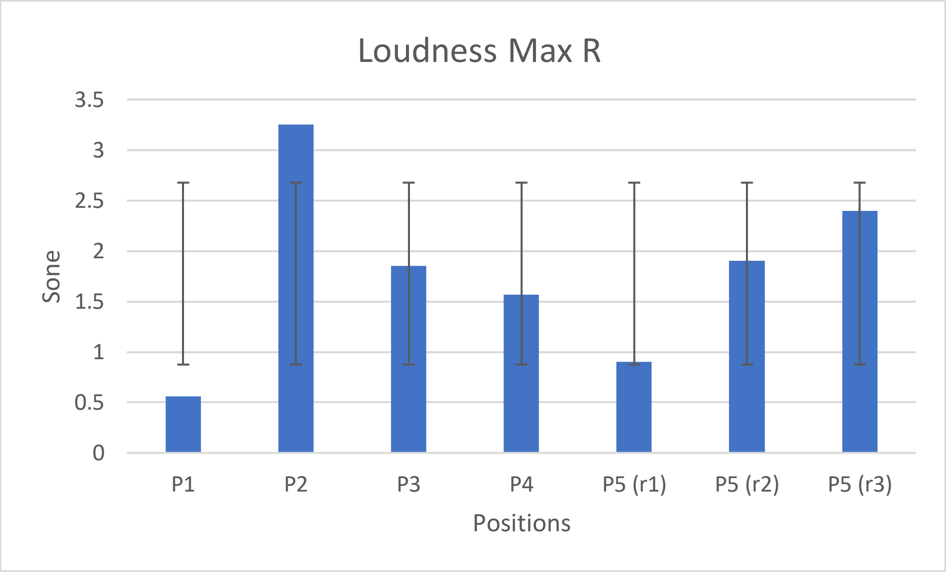

Figure 45: Loudness maximum right values - comparison between positions.

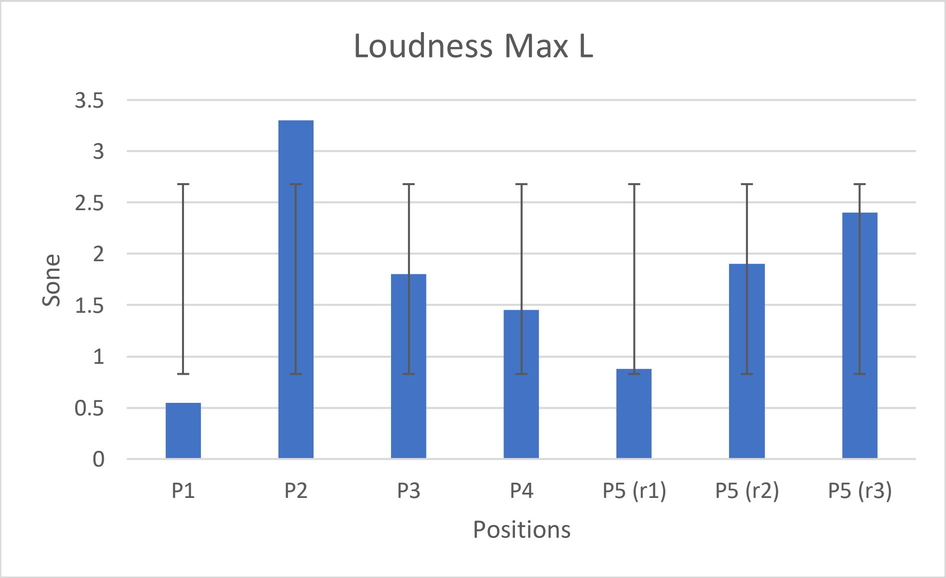

Figure 46: Loudness maximum left values - comparison between positions.

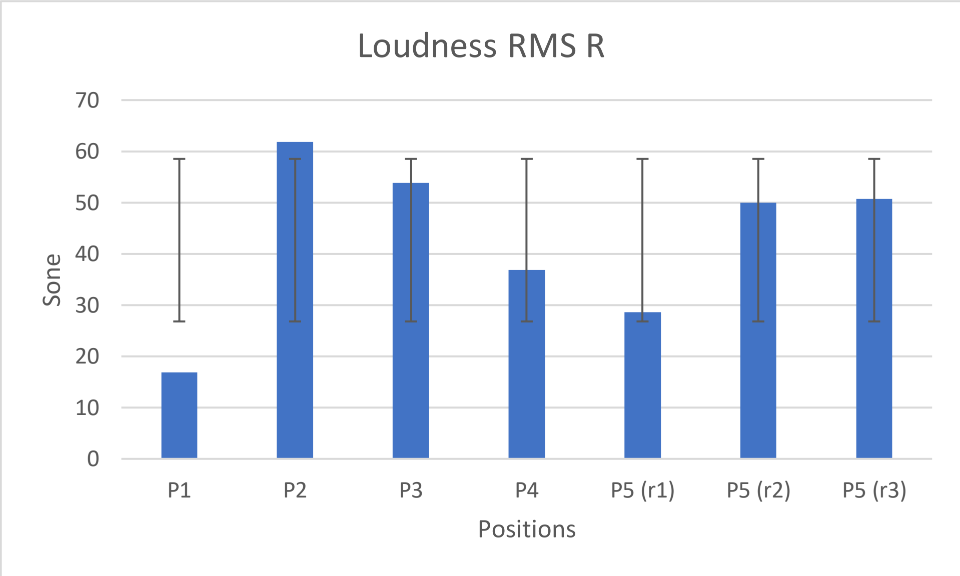

Figure 47: Loudness RMS right values - comparison between positions.

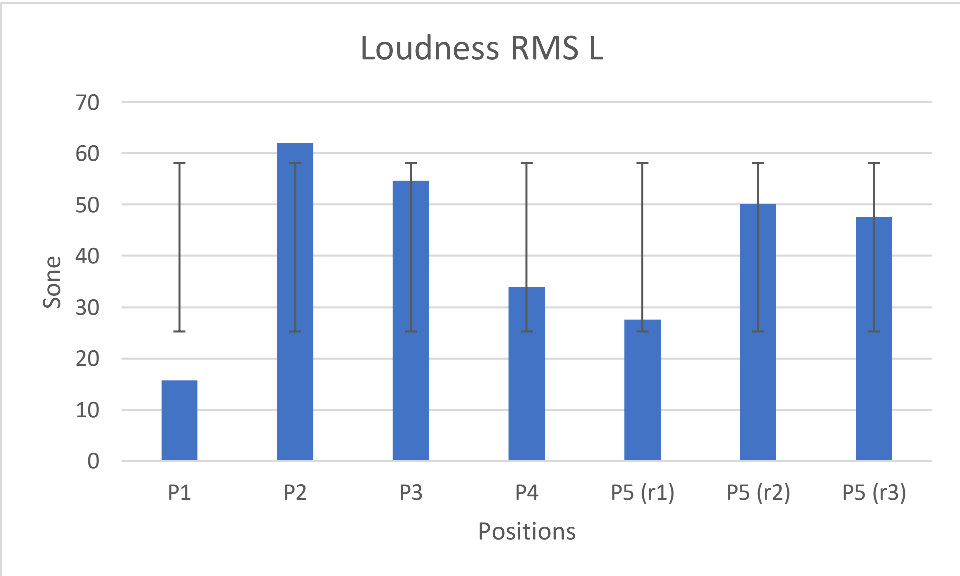

Figure 48: Loudness RMS left values - comparison between positions.

From these charts we can see that loudness plays a relevant role when there is continuous noise and overall, more sources. In fact, while in P1 we are far from every stopover's noise source, in P2 we are walking on a site where noise comes from workers who cleaning cabins, machines used to clean cabins and engines of trains, all these sources very close to each other. In P3 there is one main noise source, which is the engine of the train, the principal focus of such Position, and when we move far away, the perception of noise falls a lot. In P4 the main sources are more than one, but very distant one from the other, so their contribution could be less important than in P2. The reference position P5 has generally a loudness level higher than P1, obviously due to the contribution given by the train. But the interesting fact is that the other two P5s show loudness level always lower than P2, even if we recorded trains very close to them and they produce their typical noise described at the beginning of this work.

5.2 Sharpness values

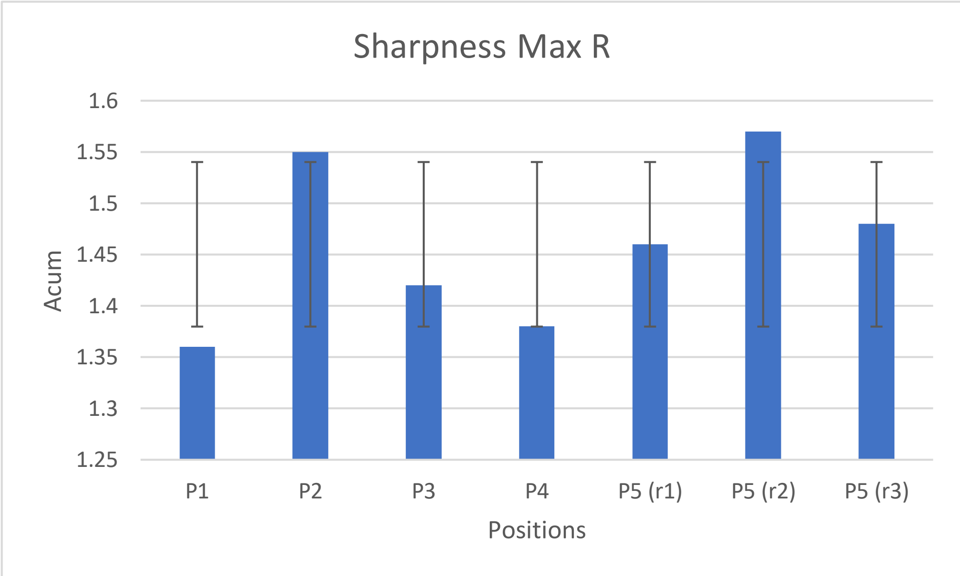

Figure 49: Sharpness maximum right values - comparison between positions.

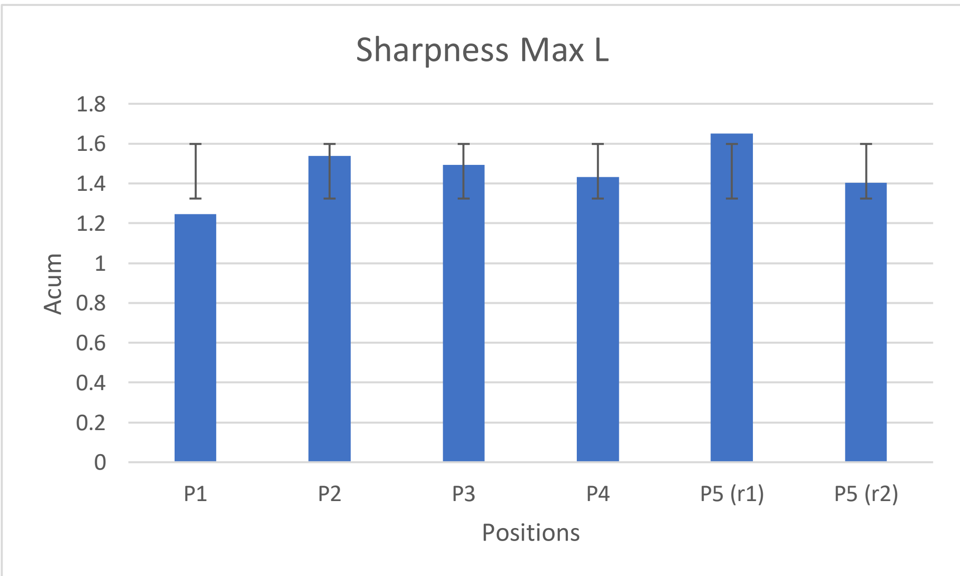

Figure 50: Sharpness maximum left values - comparison between positions.

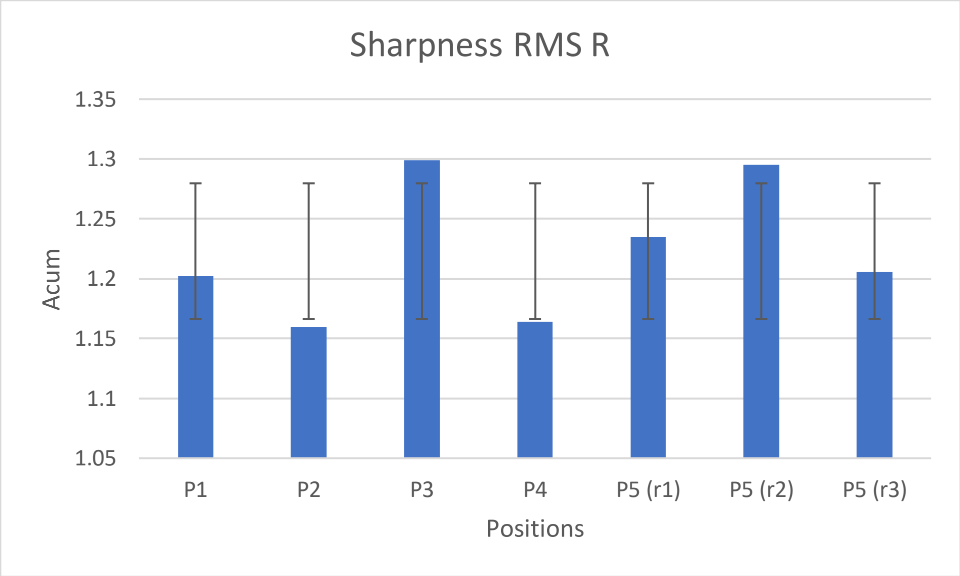

Figure 51: Sharpness RMS right values - comparison between positions.

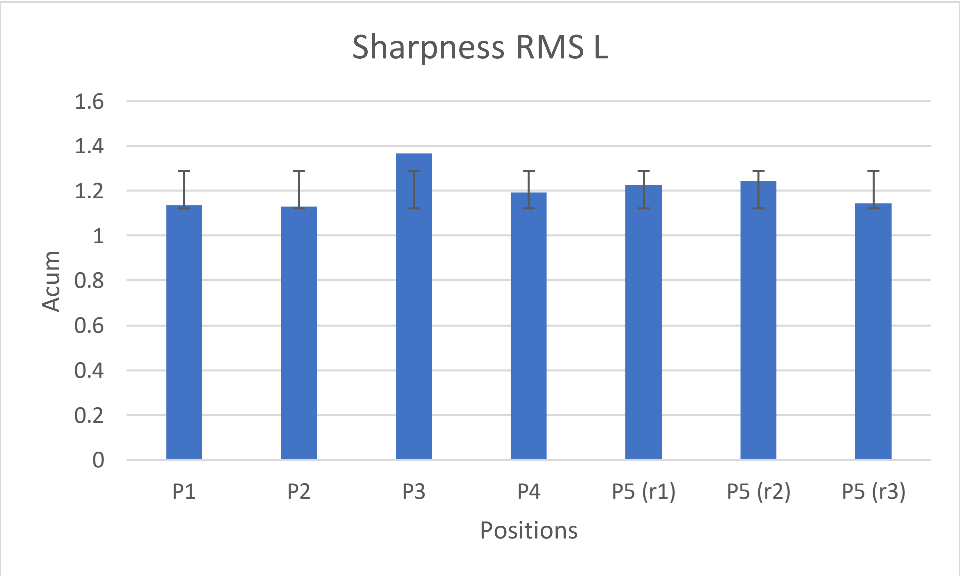

Figure 52: Sharpness RMS left values - comparison between positions.

The first characteristic which one can notice looking at the diagrams, is that sharpness behaves very differently with respect to loudness. First of all, in loudness diagrams, positions in right ear and left ear show more or less the same pattern and values quite different. We cannot say the same for sharpness: positions show different patterns if we compare the right ear with the left one. Moreover, the pattern defined by positions in right ear is more discontinuous with respect to the one in left ear, where the difference in value between positions is higher.

To conclude, Sharpness parameter depends a lot on how the head is hearing and its orientation with respect to the noise sources.

5.3 Roughness values

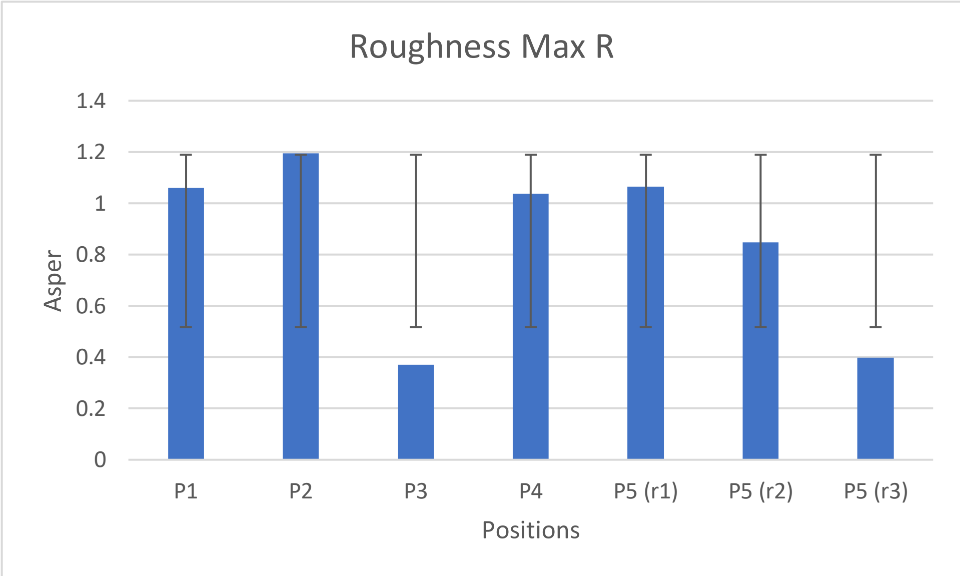

Figure 53: Roughness maximum right values - comparison between positions.

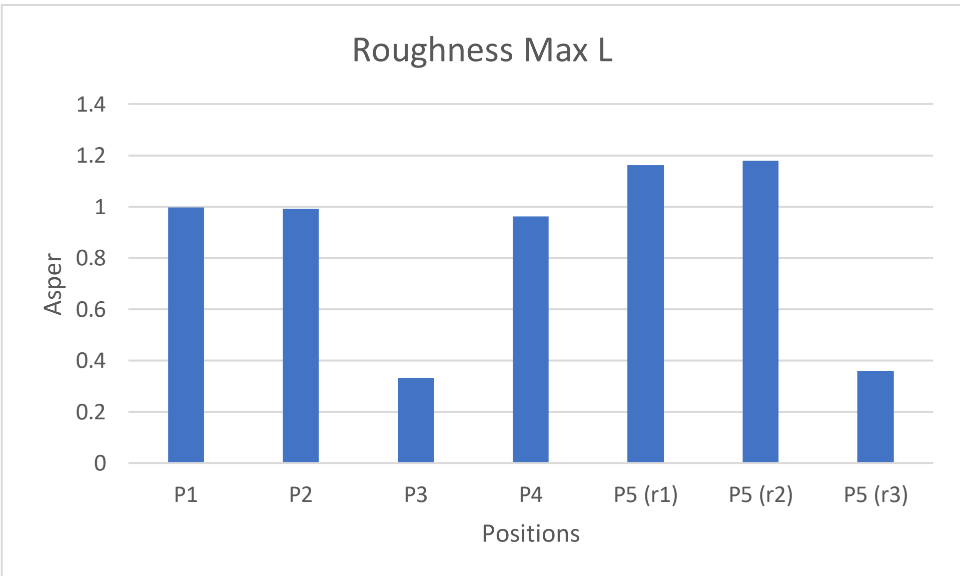

Figure 54: Roughness maximum left values - comparison between positions.

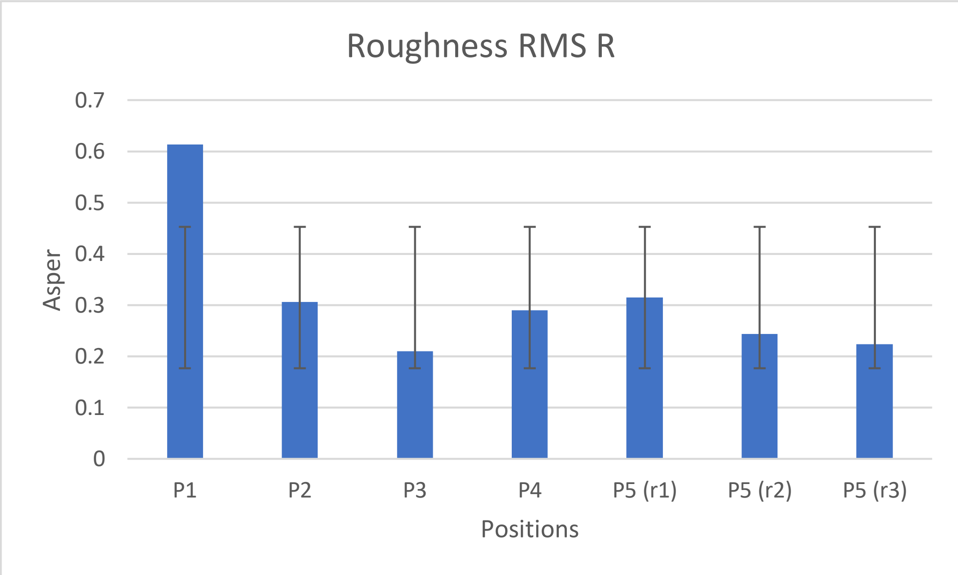

Figure 55: Roughness RMS right values - comparison between positions.

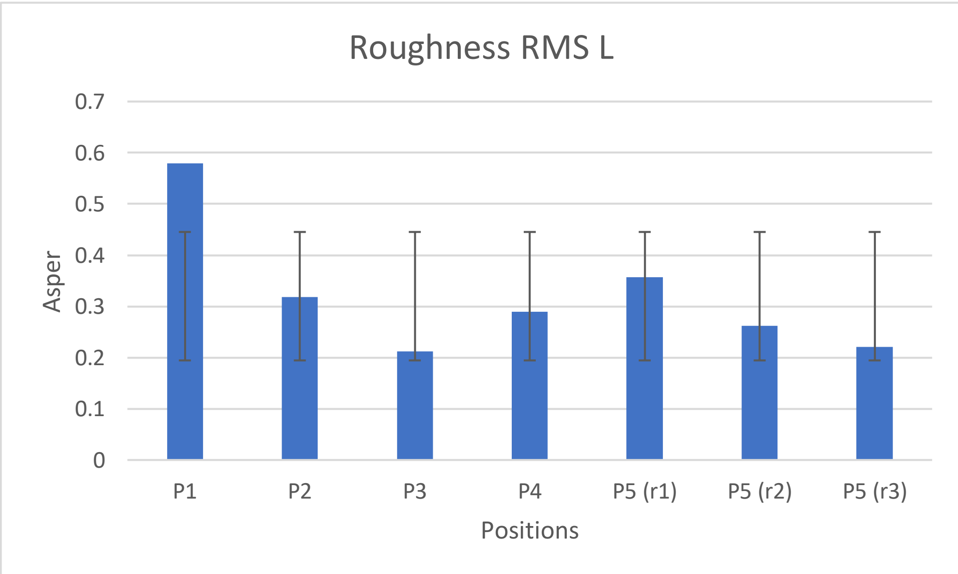

Figure 56: Roughness RMS left values - comparison between positions.

Roughness has other factors influencing its values with respect to the loudness. The common characteristic is that also the roughness shows the same patterns for each couple of diagrams (positions considered on right and left ear). But in this case, we observe that in P1 and P5 (r1), which are the reference positions, roughness values are often higher than in the other positions.

5.4 Tonality values

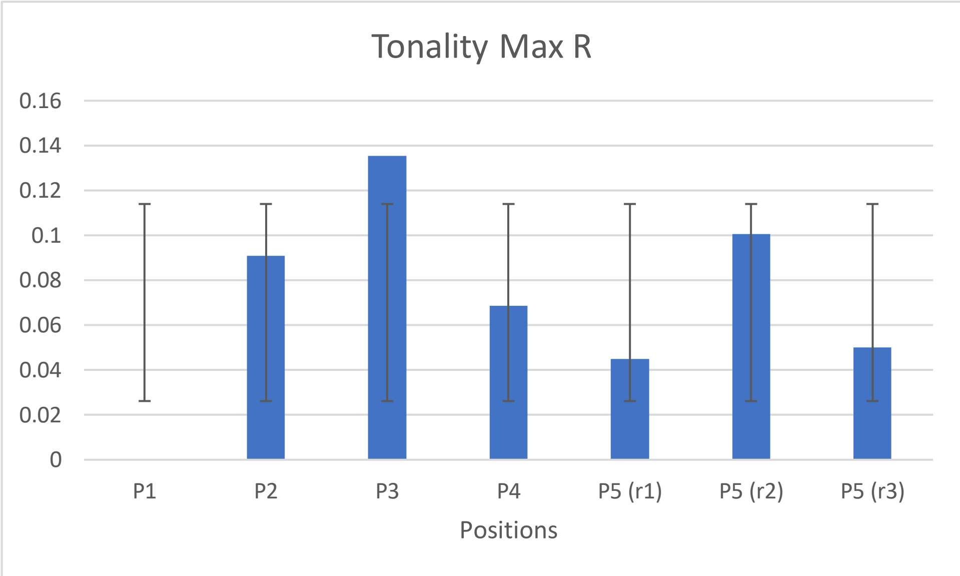

Figure 57: Tonality maximum right values - comparison between positions.

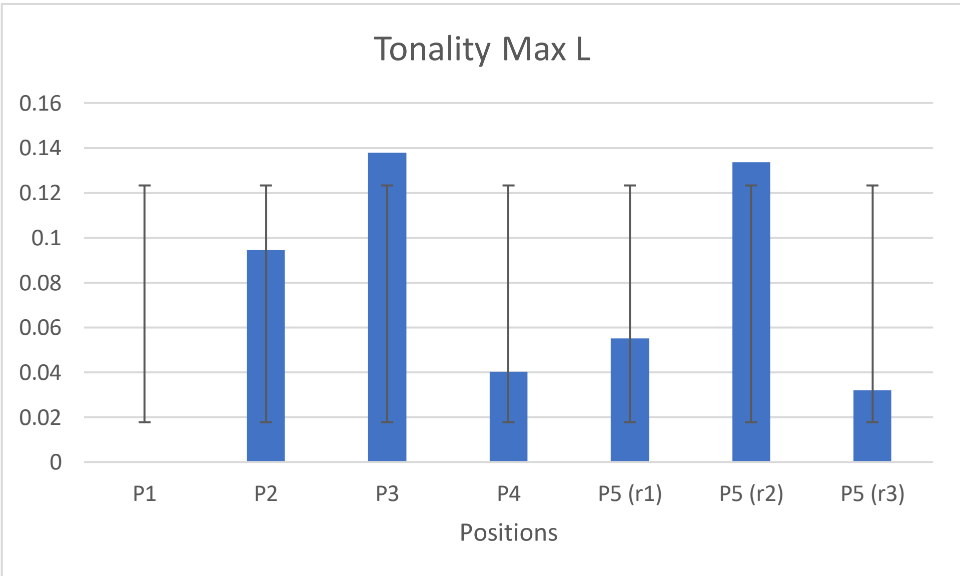

Figure 58: Tonality maximum left values - comparison between positions.

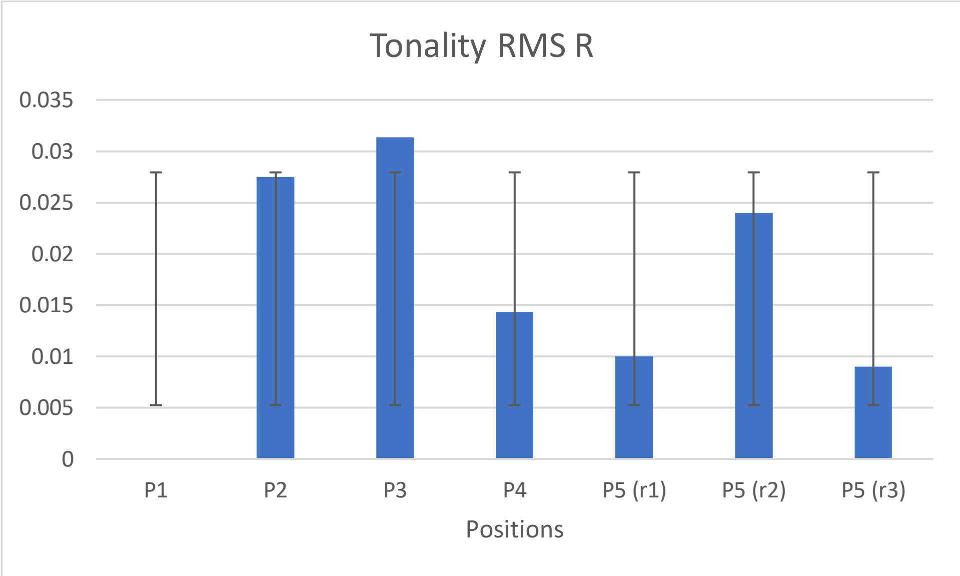

Figure 59: Tonality RMs right values - comparison between positions.

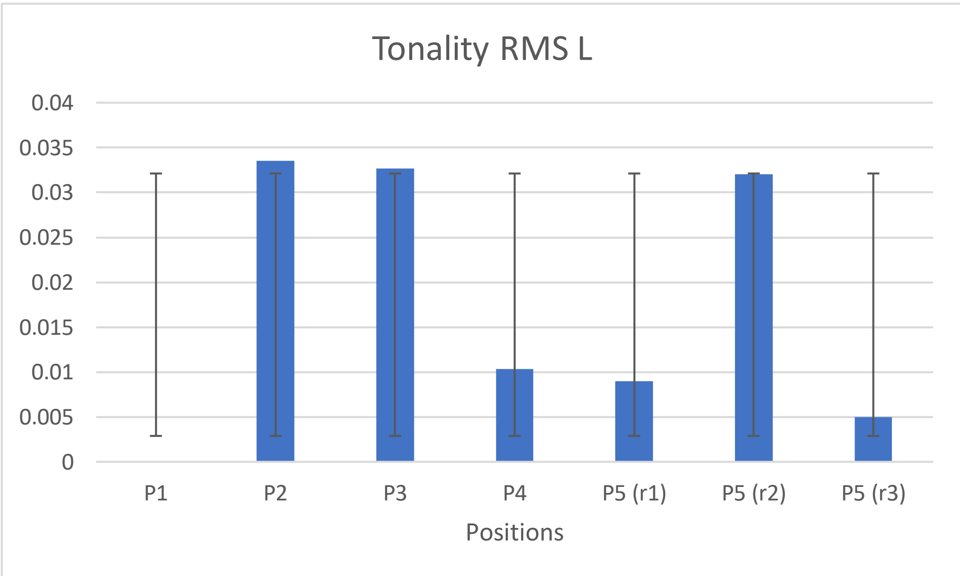

Figure 60: Tonality RMS left values - comparison between positions.

The peculiarity of tonality is that its values is always "0" in Position 1. Also, here one can see that right ear and left ear describes almost the same patterns, but not as well as the loudness and not even as roughness. The behaviour of the values here is like the one of loudness' values, lower in the reference positions and higher on the others, even if for P5 (r3) this condition is verified only in the diagram "TONALITY MAX R".

5.5 Fluctuation strength values

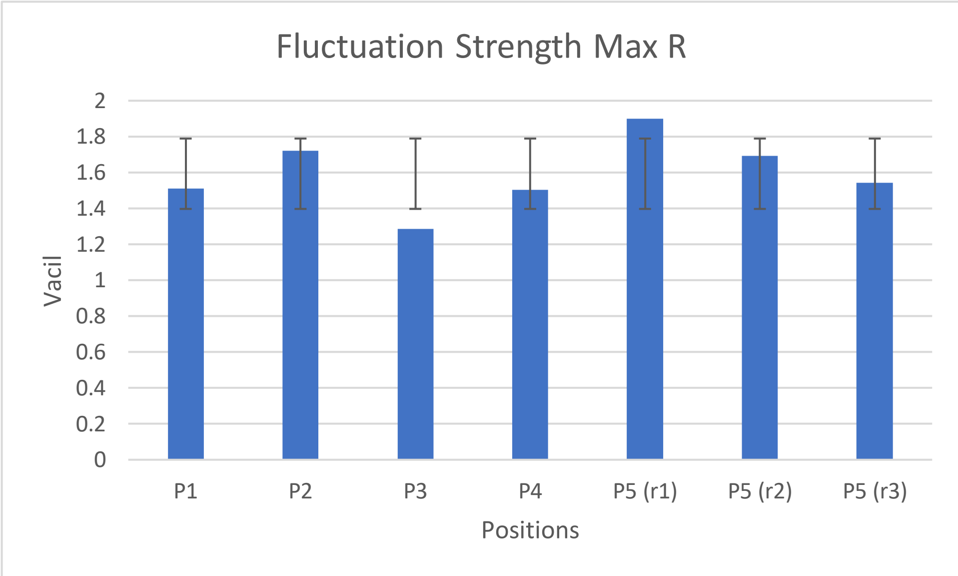

Figure 61: Fluctuation strength maximum right values - comparison between positions.

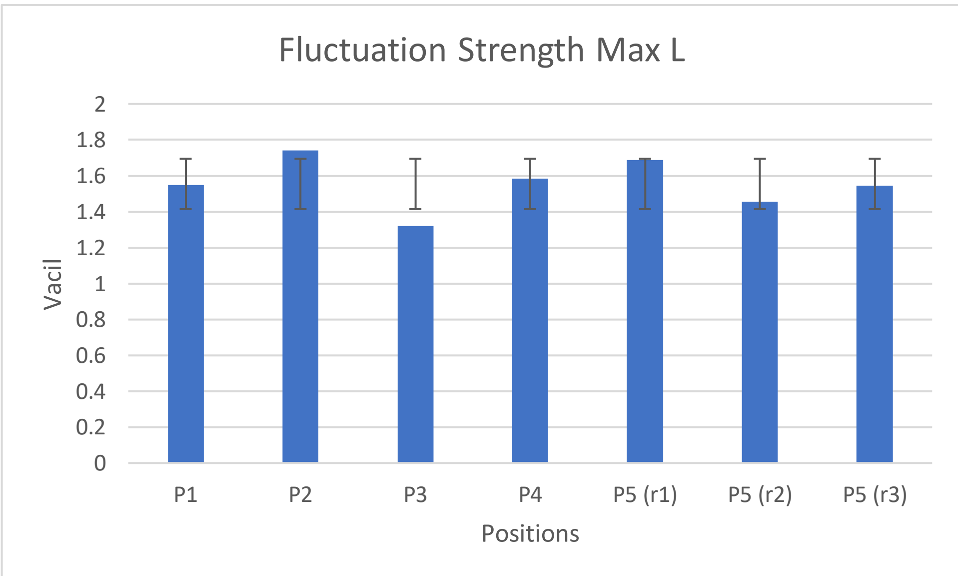

Figure 62: Fluctuation strength maximum left values - comparison between positions.

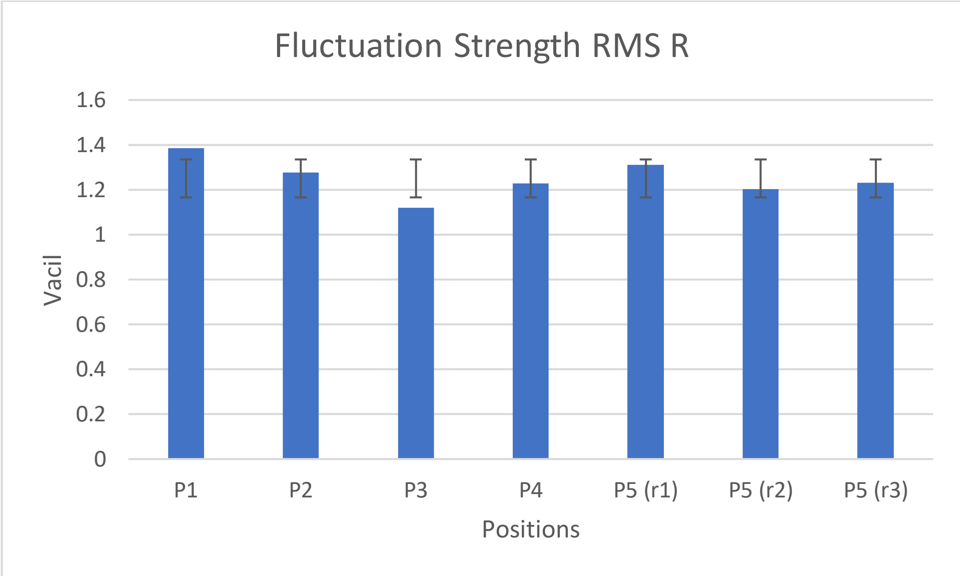

Figure 63: Fluctuation strength RMS right values - comparison between positions.

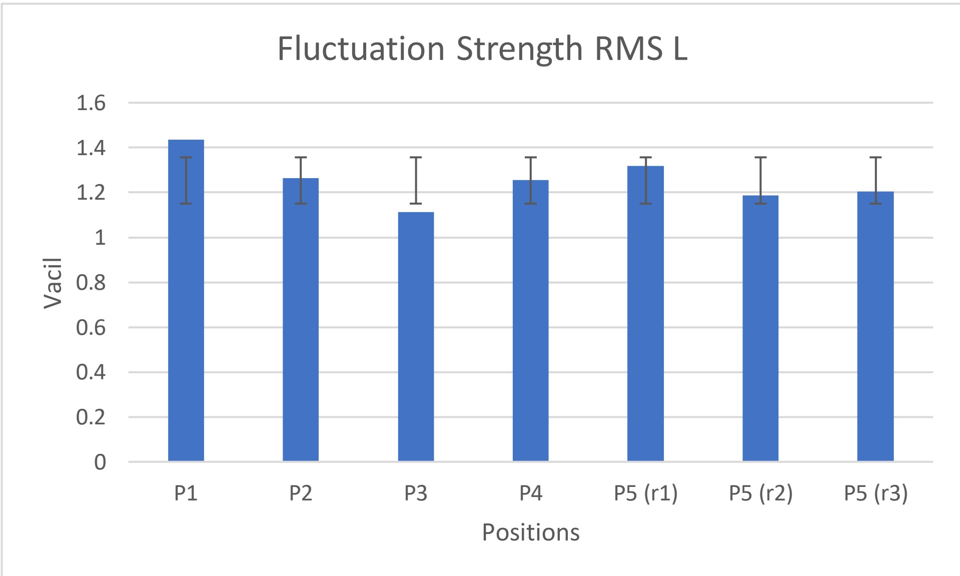

Figure 64: Fluctuation strength RMS left values - comparison between positions.

Fluctuation strength presents similar pattern too, between right and left ear, and there is not much difference in values among the positions.

This set of diagrams leads our considerations to the conclusion that on a railway stopover, the contribution given by the fluctuation strength to the noise annoyance is almost constant in the whole environment.

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