EVALUATION OF THE EFFECTIVENESS OF ACOUSTIC TREATMENTS ON A SUBWAY LINE THROUGH COMPUTATIONAL SIMULATIONS

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Abstract. *The control of the environmental impact generated by subways noise is of enormous importance to preserve the health of humanity, since the exposure to high levels of sound may cause hearing loss, hypertension and cardiac problems. This paper treats specially about the noise generated by subways, and its respective control. For the purpose of analyzing the final result of acoustic treatments that were proposed – installation of acoustic barriers – it was used a computational program developed and validated by the Acoustics and Vibration Laboratory of Faculdade de Engenharia Mecânica – FEMEC – from Universidade Federal de Uberlândia – UFU – for the simulation of the Sound Pressure Levels (SPL) on the enclosure of the subway. The results of noise impact were also obtained by analytical calculations to compare with the simulation results. Next, the noise generated by the subways impact was analyzed according to the recommendations contained in the document FTA-VA-90-103-06 (2006). For the acoustic treatment simulated on the subway rail, it was established the need of barriers that provide the minimum attenuation of 35 dB (A). The barriers used were a Compound Roof accompanied of the absorbent material ISOPET for the roof and the ISOWALL also accompanied of ISOPET for the side walls, being its transmission loss proven through the simulations on the computational program in case. Impact areas were defined for the analysis of the project effectiveness. To enable the simulation, a tridimensional model of the area was made and then, the Sound Power Levels (SPL) of the sound source and the materials properties of the barriers were identified. Performed the simulations and the calculations, it was found that the results obtained were really close, with maximum errors of 7 dB, justifying the simplifications adopted in the calculations. It was also proved that the final situation generates a moderate or a non-impact on the analyzed areas.*

Keywords*: Metropolitan Transport, Acoustic, Environmental Impact*

1. INTRODUCTION

In metropolitan cities, the traffic is responsible for a large quantity of noise pollution. The control of environmental impact generated is of paramount importance to preserve the health of human being, since that the exposure to high levels of noise can cause hearing loss, hypertension and cardiac problems. Exposure limits to noise are imposed to preserve the physical integrity of the citizens.

This work treats specially about the noise generated by subways, and its respective control. The noise of these vehicles comes from: the interaction between the wheel and the rail; the structural vibrations; the vehicle's body vibrations; the propulsion system; the aerodynamic drag; among other factors. The control of the emitted noise can be made by various ways, particularly in this work it was chosen to use acoustic barriers.

In order to analyze the final result of the acoustic treatments that were proposed, it was used a computational program developed and validated by the Acoustics and Vibration Laboratory of the Faculdade de Engenharia Mecânica (FEMEC) from Universidade Federal de Uberlândia (UFU) for the simulation of the Sound Pressure Levels (SPL) on the surroundings of the subway. It was also obtained the results of the noise impact through analytical calculations, to compare with the simulation results. For the evaluation of the sound impact generated by the trains, it was used the recommendations contained in the document FTA-VA-90-103-06 (2006).

2. OBJECTIVE

The objective of this work is to present the simulation and calculations of the influence area of a subway after the acoustic treatments, evaluating the effect caused in certain controlled points and classify the environmental impact of the noise generated by the subway trains.

3. METHODOLOGY

3.1. Sound Level Estimative on Receptors Through Computational Simulations.

This work presents the evaluation of a subway line stretch that passes through a region above the ground level, named elevated rail. That is, the subway leaves the underground and enters in this elevated region, which is near to communities. For the operation of this subway on the elevated stretches some acoustic solutions are needed to attend some norms established by the FTA-VA-90-103-06 (2006) document in respect of generation of noise. For that, it was simulated the closing of the subway line with acoustic barriers. The roof was closed with the material named Compound Roof with the absorbent material ISOPET, and on the side walls was installed the ISOWALL also with ISOPET. These materials are developed by the company ISOBRASIL for acoustic treatments. Figure 1 presents the transversal section of the subway line, showing how the barriers will be installed. It is important to bounce that it will be evaluated the complete closing condition of the line and another situation without the installation of the top cover (Compound Roof and ISOPET). The support structure of the elevated is developed with concrete.

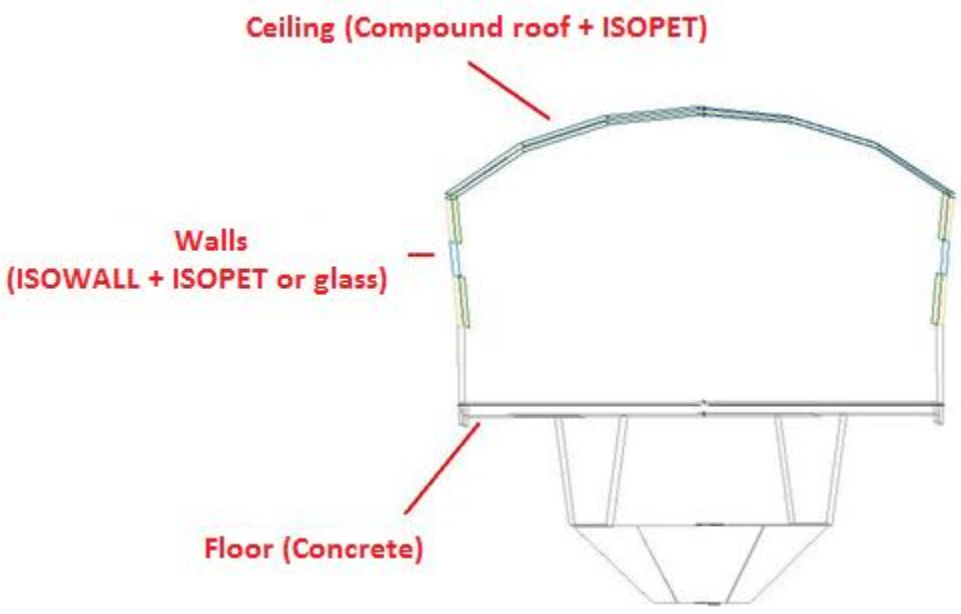

Figure 1. Cross section of the subway line with the acoustic barriers installed.

From the analyses of local noise emission on subway lines, it was established that the minimum total loss of transmission must be of 35 dB(A). In order to prove this attenuation, the computational program was used simulating the pressure isocurves generated by the sources, considering a critical situation: the crossing of two subway trains, each with a speed of 100 Km/h. Figure 2 presents the results of this simulation, being used the values of Sound Power Levels (SWL) specified on Tab. 1. This values were taken from Fig. 2, which presents the spectrum of Sound Pressure Levels (SPL) generated by trains with different speeds of operation, measured from a distance of 10 meters away from the rails.

Table 1. SWL values estimated for a train with a speed of 100 Km/h, per octave band.

Central Frequency (Hz)	63	125	250	500	1000	2000	4000	8000
SWL (dBA)	89	82	79	93	94	89	83	83

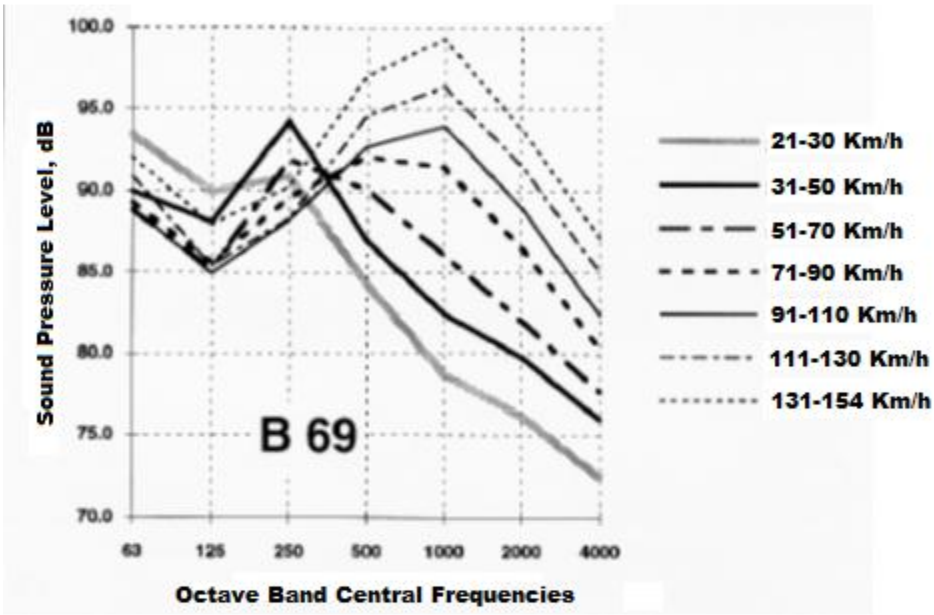

Figure 2. Frequency spectrum used for the estimation of the SWL values of the subway for simulations and calculations.

From the analysis of Fig. 3, the values of Sound Pressure Levels at the external (A, B and C) and internal points (D) are approximately 51.5 dB(A), 60.4 dB(A), 50.3 dB(A) e 92.0 dB(A), respectively. From this points, the attenuations found vary from 31.6 to 41.7 dB(A), which is close to the minimum values established, considering that the critical situation of two subways crossing was applied, being potentiated the noise level generated. It must be accentuated that errors of up to 3 dB are acceptable in acoustic simulations.

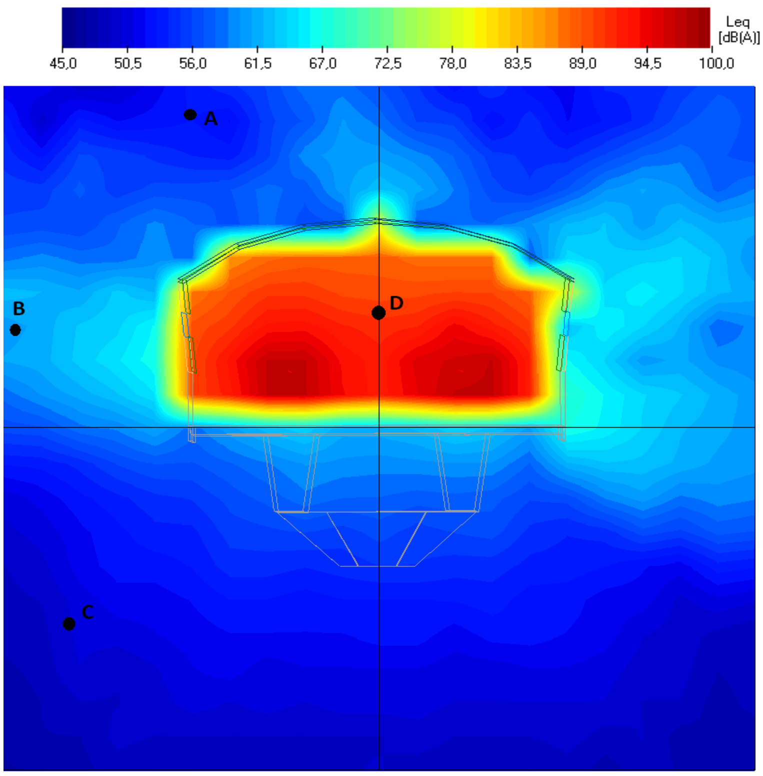

Figure 3. SPL simulated on the computational program considering the situation of two subway trains crossing at a speed of 100 Km/h in the acoustic closing section.

For the treatments efficiency analysis on the influence zone, it was established impact areas, which normally are characterized by residential and office areas, both nearby of the subway line. Figure 4 presents the surroundings of the subway showing the impact areas simulated.

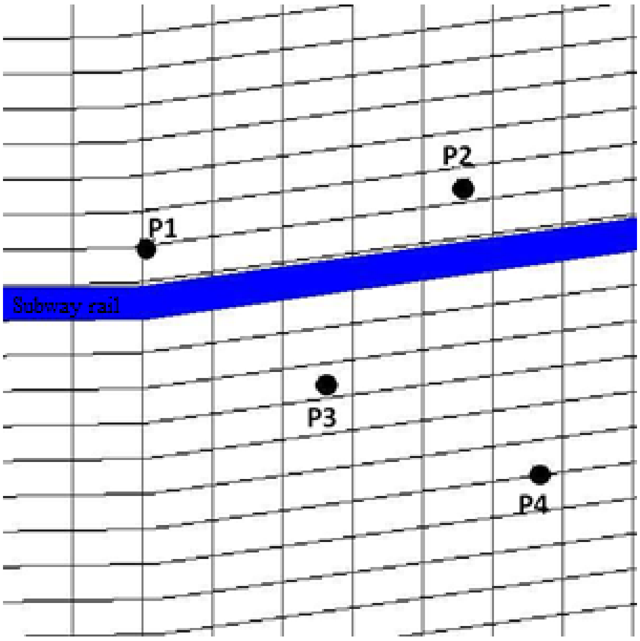

Figure 4 – Determined impact areas for analysis.

On Fig. 4 the blue line represents the elevated zone where the subway transits. The mesh presented is used with the purpose to facilitate the location of the dots. The direction changes on the mesh represent the simulated relief.

With the impact areas defined, a tridimensional acoustic model of the place was built for the accomplishment of the simulation. Figure 5 presents the model used.

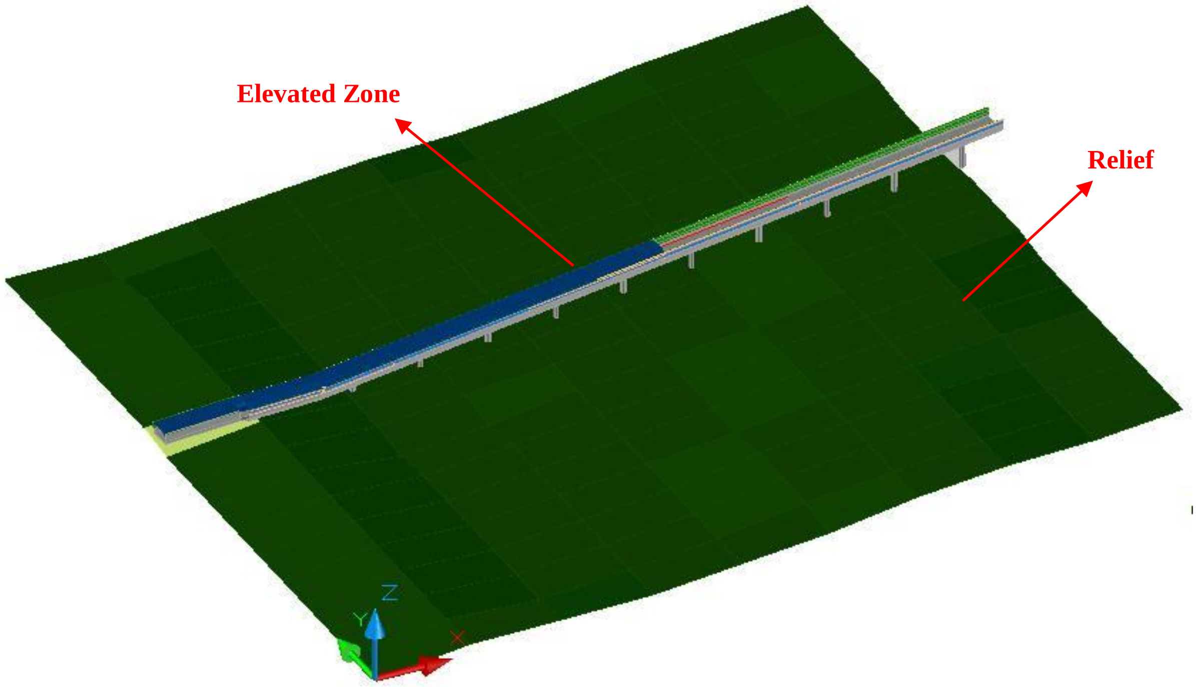

Figure 5 – Tridimensional acoustic model of the subways influence zone.

For the construction of the model, it was developed a layout considering the local relief and the original subway line project dimensions. In the simulations, besides the SWL of the sources, it is also required the acoustic barriers properties. Tab. 2 and Tab. 3 presents the values obtained for the Transmission Loss, in octave band in dB(A) and the absorbent materials indexes represented by its percentage, respectively.

Table 2. Transmission Loss values (dB(A)) in octave band of the materials used on the barriers.

Material	Central Frequencies (Hz)							
	63	125	250	500	1000	2000	4000	8000
ISOWALL	18.1	18.1	20.1	28.0	32.3	39.0	41.0	41.0
ISOPET	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Compound Roof	43.8	43.8	53.8	63.8	69.9	79.9	82.1	88.6
Concrete	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0

Table 3. Absorbent indexes values (%) in octave band of the materials used on the barriers.

Material	Central Frequencies (Hz)							
	63	125	250	500	1000	2000	4000	8000
ISOWALL	1	2	2	3	4	5	7	7
ISOPET	29	29	55	82	91	88	82	82
Compound Roof	2	2	2	3	4	5	7	7
Concrete	2	2	2	3	4	5	5	6

3.2. Analytical Calculation of the Noise Levels on the Receptors.

Initially it is necessary to cognize the noise levels caused by the subway trains. The noise levels evaluation was made such as the procedure presented on the FTA-VA-90-103-06 (2006) document, which is based on the reference noise exposure level (SEL_{ref}), which represents the sound energy generated by the train's traffic in standard conditions.

Before the calculation of SEL_{ref} it is necessary to determine the noise exposure level measured during the passage of the train (SEL_{meas}) using the data presented in Fig. 2, providing a L_{eq} value of 101 dB(A). For the noise measurements it was stipulated a train speed of 70 Km/h. The sound exposure level was calculated form Eq. (1) considering that the passage of the train had a duration of t = 7s.

$$SEL_{meas} = L_{eq} + 10.\log(t) \quad (1)$$

The reference sound exposure level (SEL_{ref}) represents the standard value for a distance of D = 15m far from the rails, a number of cars N_{cars}= 1 and an operation velocity of S = 80 Km/h. To calculate SEL_{ref} it was used Eq. (2).

$$SEL_{ref} = SEL_{meas} - 20.\log\left(\frac{Smeas}{80}\right) + 10\log\left(\frac{Dmeas}{15}\right) - 10\log(Ncars) \quad (2)$$

In Eq. (2) the adopted speed value of the train during the noise measurements (Smeas) was 70 Km/h; the measurement distance from the line (Dmeas) was of 5m; and the number of train cars (Ncars) was 6.

It is known that the environmental impact caused by the trains depends not only of their transit, but of its duration passing through a stipulated zone (which depends on the number of train cars), of the traffic volume (number of trains per hour trafficking) and of the train's transit speed. Therefore, the environmental impact caused by noise should be evaluated according to the hourly equivalent level (L_{eqh}) or to the day/night sound equivalent level (L_{dn}), which represents properly these factors.

The hourly equivalent level (L_{eqh}) is given by the Eq. (3), with the number of cars equal to 6 and a train speed of 100 Km/h. The values of the traffic volume admitted were: 50 trains per hour during the day, and 30,3 trains during the night. With these traffic volume the day/night equivalent levels are obtained ($L_{eqh,d}$ e $L_{eqh,n}$).

$$Leqh = SEL_{ref} + 10\log(Ncars) + 20\log\left(\frac{S}{80}\right) + 10\log(V) - 35{,}6 \quad (3)$$

Containing the $L_{eqh,d}$ and $L_{eqh,n}$ values, the L_{dn} factor can be calculated through Eq. (4).

$$Ldn = 10\log\left(15.10^{\frac{L_{eqh,d}}{10}} + 9.10^{\frac{L_{eqh,n}}{10}}\right) \quad (4)$$

With this data, the attenuation obtained from the noise propagation of the source to the receptors can be calculated. In this work, a critical situation was considered, the propagation is given on an opened field, since the distribution of the buildings and constructions can be modified over time. Therewith, it will be considered only the geometric attenuation, which is the attenuation caused by the distance between the receptor and the source, besides the attenuation caused by the subway's enclosure.

The geometric attenuation is given by Eq. (5), being D the distance between the source and the receptor. The values of D for each control point adopted are explicit on Tab. 4.

$$Ageom = 10.\log\left(\frac{D}{15}\right) \quad (5)$$

Table 4. Distance from the subway line to the control points for the geometric attenuation calculation.

Control Point	Distance (m)
P1	30
P2	38
P3	58
P4	80

To determine the attenuation obtained from the subway enclosure, the first step is to set the sound level increase inside the region closed with acoustic barriers, because of the reflective and absorbent surfaces, and then determine the transmission loss from inside to outside of the closing.

The increase of the sound level on the interior depends on the barriers material's absorption. After the Noise Power Level's (NW_{dir} = 109 dB) determination, the local average absorbent index is calculated, by the Eq. (6).

$$\alpha_m = \frac{\sum S_i \alpha_i}{\sum S_i} \quad (6)$$

In Eq. (6), S_i is the area of each material and α_i is the acoustic absorbent index of a respective material. These values are exposed on Tab. 5, for each material.

Table 5. Absorptive and Transmission areas, and its respective absorption and transmission loss indexes.

Material	Absorptive Area (m²)	Absorption Index (α)	Transmission Area (m²)	Transmission Loss (dB(A))
Ceiling Acoustic Panel	1383.3	0.8	1383.3	35
Side Acoustic Panel	522.0	0.8	522.0	35
Glass	-	-	182.7	35
Concrete Floor	-	-	1239.8	50
Beginning and Ending	66.1	1	-	-

The complete absorption of the acoustic enclosure is calculated with Eq. (7) (GERGES, 2000).

$$A = -\sum S_i.\ln(1-\alpha_i) \quad (7)$$

The sound level of the reflected sound on the interior of the enclosure is given by Eq. (8).

$$L_r = NW_{dir} + 10.\log\left(\frac{4}{A}\right) \quad (8)$$

The sound level inside the enclosure is calculated by Eq. (9).

$$L_d = NW_{dir} + 10\log(D) + 10\log(L_r) - 5 \quad (9)$$

The total sound level on the interior of the enclosure is obtained by Eq. (10).

$$L_{tot} = 10\log\left(10^{\frac{L_d}{10}} + 10^{\frac{L_r}{10}}\right) \quad (10)$$

The sound level increase on the enclosure's interior according to their absorption characteristics is given by the difference between L_{tot} and L_d, like showed in Eq. (11).

$$A_{abs} = L_{tot} - L_d \tag{11}$$

The next step is the determination of the Transmission Loss caused by the enclosure. The attenuation in this case depends on the transmission indexes of the enclosure's components, and of its area. The transmission index of a particular component can be determined from its transmission loss, like showed in Eq. (12).

$$\tau = 10^{-\frac{PT}{10}} \tag{12}$$

With the transmission indexes of each component in hands, the average transmission index can be found through Eq. (13).

$$\tau_m = \frac{\sum \tau_i S_i}{\sum S_i} \tag{13}$$

In Eq. (13) S_i represent the areas of each component, and τ_i represent the transmission indexes of each component, calculated from Eq. (12). The Transmission Loss and the area of each component are exposed on Tab. 5.

The total Transmission Loss is calculated by Eq. (14).

$$PT_m = 10 \log \left(\frac{1}{\tau_i}\right) \tag{14}$$

With the noise levels generated by the subway train determined on the sound propagation way to the receptor and the attenuation components values, it is possible to calculate the sound level caused by each source on the receptor through Eq. (15).

$$L_{rec,i} = L_{fon,i} - A_{geom,i} + A_{abs,i} - PT_m \tag{15}$$

Where $L_{fon,i}$ is the sound level in equeivalent value (L_{eq} ou L_{dn}) produced by the source from 15m away from the rails; $A_{geom,I}$ is the geometric attenuation from the source to the receptor; $A_{abs,I}$ is the sound level increase inside of the enclosure; and $PT_{m,I}$ is the attenuation due to the transmission loss of the enclosure.

The total sound level on the receptor is obtained summing the effects of all sound sources on the receptor, calculated by Eq. (16).

$$L_{rec} = 10 \log \left(\sum 10^{\frac{L_{rec,i}}{10}}\right) \tag{16}$$

3.3. Impact Evaluation Criterion.

After obtaining the results, the SPL values founded on the control points must be evaluated by the FTA-VA-90-103-06 (2006) criterion through Tab. 4, defining the local impact level.

On Tab. 6, the L_{amb} values represent the possible ambient noise levels that may be found on the impact areas. Considering the treated zone, characterized by the presence of offices and residences, it was chosen the L_{amb} and the impact area categories showed on Tab. 7. It is important to emphasize that the L_{amb} values are defined from the ambient noise level commonly found in areas similar to the analyzed area.

Table 6. Impact degree expected on the receptors due to the project sound level (L_{rec}) and ambient noise (L_{amb}).

Ambient Noise Level L_{amb} (dBA)	Expected impact with the sound level on the receptor					
	Category 1 or 2			Category 3		
	None	Moderate	Severe	None	Moderate	Severe
57	<57	57-62	>62	<62	62-67	>67
58	<57	57-62	>62	<62	62-67	>67
59	<58	58-63	>63	<63	63-68	>68
60	<58	58-63	>63	<63	63-68	>68
61	<59	59-64	>64	<64	64-69	>69
62	<59	59-64	>64	<64	64-69	>69
63	<60	60-65	>65	<65	65-70	>70
64	<61	61-65	>65	<66	66-70	>70
65	<61	61-66	>66	<66	66-71	>71
66	<62	62-67	>67	<67	67-72	>72
67	<63	63-67	>67	<68	68-72	>72
68	<63	63-68	>68	<68	68-73	>73
69	<64	64-69	>69	<69	69-74	>74
70	<65	65-69	>69	<70	70-74	>74
71	<66	66-70	>70	<71	71-75	>75
72	<66	66-71	>71	<71	71-76	>76
73	<66	66-71	>71	<71	71-76	>76

Table 7. L_{amb} values (dB(A)) and established impact area's categories.

Point	Classification	L_{amb} (dBA)
P1	2	60
P2	2	57
P3	2	57
P4	3	73

4. RESULTS

After simulating the analyzed stretch, the isocurves showed on Fig. 6 were obtained.

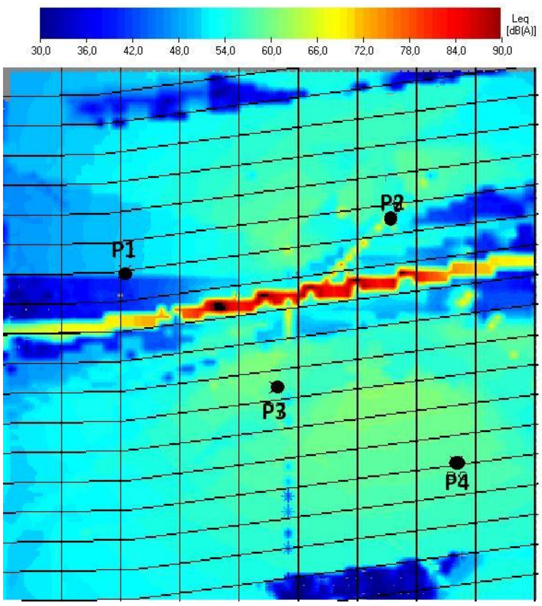

Figure 6. Sound Pressure Isocurves of the simulated subway stretch.

From the analysis of Fig. 6, the SPL values on the impact areas are determined, as showed by Tab. 8.

Table 8. SPL simulated values on the determined impact areas.

Point	NPS (dBA)
P1	51.3
P2	54.7
P3	57.3
P4	58.2

The results obtained through the analytical calculation are exposed on Tab. 9.

Table 9. Results of the calculations of the mobile sources' sound progation.

Point	Source	$L_{eqh,D}$	$L_{eqh,N}$	L_{dn}	NW_{dir}	A_{abs}	PT_m	A_{geom}	$L_{eqh,Drec}$	$L_{eqh,Nrec}$	L_{dnrec}	L_{eq}
P1	1	99.3	97.1	98.5	109	5.4	37.0	15.1	52.6	50.4	51.8	55.0
P1	2	99.3	97.1	98.5	109	5.4	37.0	14.5	53.2	51.0	52.4	
P2	1	99.3	97.1	98.5	109	5.4	37.0	15.6	52.1	49.9	51.3	54.0
P2	2	99.3	97.1	98.5	109	5.4	37.0	16.0	51.6	49.5	50.8	
P3	1	99.3	97.1	98.5	109	5.4	37.0	17.8	49.9	47.7	49.1	52.0
P3	2	99.3	97.1	98.5	109	5.4	37.0	17.5	50.2	48.0	49.4	
P4	1	99.3	97.1	98.5	109	5.4	37.0	19.2	48.5	46.3	47.7	51.0
P4	2	99.3	97.1	98.5	109	5.4	37.0	19.0	48.7	46.5	47.9	

The errors between the calculated and simulated values vary from approximately 1 to 7 dB(A). The biggest errors are found on points 3 and 4, which explains the fact that the relief wasn't considered on the analytical calculations.

Considering the SPL values obtained, it was made an impact evaluation by the criterion cited on the methodology. Tab.10 presents the impact level of each point.

Table 10. Impact Levels on the Control Points.

Point	Simulated Impact	Calculated Impact
P1	None	None
P2	None	None
P3	Moderate	None
P4	None	None

5. CONCLUSION.

For the acoustic treatment on the simulated subway line, it was established the need of acoustic barriers that provided a minimum attenuation of 35 dB(A). The chosen materials were the Compound Roof accompanied by the absorbent material ISOPET for the roof and ISOWALL also accompanied by ISOPET for the side walls.

Proving their attenuation, it was performed simulations on the computational program, which showed that the acoustic barriers provided a decay ranging between 31.6 and 41.7 dB(A), ensuring the effectiveness of themselves.

In order to simulate the subway stretch, it was developed a tridimensional model of the site, considering the relief, for realistic results. In possession of the model, the source SWL values and the used materials acoustic properties were estimated.

It was also performed analytical calculations to estimate the noise levels that achieve the receptors on the chosen control points. The results obtained were compared to the simulated values. It was verified that the results were very close, but in two control points, the errors were of 5 and 7 dB. This can be explained by the fact that the path of sound propagation of these two points has an accentuated relief, which was considered only on the simulations.

Performed the simulations, the SPL values were obtained for the previously determined impact areas. From the ambient noise level of these areas and considering the evaluation criterion established by the FTA-VA-90-103-06 (2006) document, it was possible to determine the noise impact level generated by the subway train. This analysis showed that the final situation generates a moderate or none impact on the analyzed areas, proving the effectiveness of the acoustic solutions proposed, qualifying its application.

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