AN INNOVATIVE PROPOSAL TO REDUCE NOISE LEVEL AT ALCAZABA TUNNEL IN MALAGA (SPAIN)

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Abstract
This paper aims to find a solution to mitigate existing noise inside the Alcazaba tunnel, where coexists traffic and pedestrian lanes. Unacceptable noise levels for pedestrians were found within the tunnel and different proposals were analysed by acoustic simulation. Finally, the construction of a gallery as an enclosure to segregate pedestrian and traffic is proposed as the only option that complies with noise regulation while allowing pedestrian transit. Also, a cultural alternative use is proposed to this corridor so, in this way, crossing the tunnel will be much more pleasant.

Keywords: Noise mitigation, acoustic simulations, tunnel, action plans, environmental noise.

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1 Introduction

It is widely recognized that environmental noise has become one of the biggest sources of discomfort in modern societies as well as a source for citizens' complaints and occasional lawsuits. We are exposed to it in our homes, on the street, at work, when we use transport vehicles and even in our leisure time. For most citizens who live in developed countries, noise pollution today is omnipresent but thought essential for our life style. Therefore, many people believe that noise pollution is really difficult to deal with and perhaps an unavoidable consequence of development and technological progress. Cultural factors are to be considered also. A compromise between complex factors must be adopted, using a sustainability approach.

Different investigations done over the last decades by many authors around the world have shown that noise pollution clearly affects human health, producing a long list of highly diverse physiological and psychological disorders, whose severity varies greatly with the specific conditions in each case.
This apparent contradiction of opinions must be solved by the different administrations, which have to regulate emissions and set the corresponding limits for them, without slowing technological development, this will not be at the expense of the citizens' health.

2 Description of the problem

The Alcazaba tunnel is located in the city of Malaga, in the south of the Iberian Peninsula, bordered by the Mediterranean Sea, connecting the access from the historic centre and East Malaga, joining Alcazabilla Street and The Park.

This tunnel is built with a reinforced concrete curved wall, with a polished smooth surface. This makes the enclosure to have highly reflective characteristics. Inside, there are four lanes, each 3 meters wide and two sidewalks for pedestrians. The tunnel has a total length of 253 meters and is slightly curved. Since its construction, the tunnel has presented a special acoustic problem. Because of its geometry and its surface material characteristics, a very high noise level is reached inside this enclosure (keeping in mind that this tunnel is not only for road traffic but also for pedestrians). Pedestrians are exposed to an excessive noise level and it is superior to any congested urban road. This suggests that a problem of increasing noise intensity by successive internal reflections was not considered in the initial project.

Figure 1 – Alcazaba Tunnel.

Sound propagation of noise in cities has been the subject of extensive research. Lu et al. [1] described the development of a numerical model for the prediction of sound fields in city streets, concluding that the incoherent model was accurate if the width of a street is greater than 10 m. In addition, there has been considerable research into the physical phenomena of sound propagation in long enclosures. Hübelt et al. [2] performed numerical and analytical investigations on the specific sound propagation effects in and around tunnels. Also, using two-dimensional hard rough surfaces to reduce noise levels in traffic tunnel has been examined by Kan Law et al. [3]. In this paper a simplified method based in the ray theory widely used in outdoor acoustic is proposed to study different mitigation noise measures to reduce the current noise levels inside the Alcazaba tunnel.

3 Acoustic modelling and noise

In order to properly evaluate the reflection processes occurring inside the tunnel, a digital model of the tunnel was made by digitizing and subsequent treatment with an acoustic program.

First, based on the design drawings of the tunnel, a 3D modelling was performed with the software Autocad 2013®.

The acoustic modelling was performed with the EASE® program, where two planes (audience areas) along the sidewalk stretches were introduced at a height of 1.55 meters, which is considered as the average location of the person's ears.

In order to evaluate existing sources of noise, the volume of traffic passing through the tunnel should be analysed, taken into consideration that both the number of vehicles and the characteristics thereof are variable. Statistics from the Mobility Area of the City Council of Malaga were taken as a basis [4].

The latest data about vehicles intensity available on the website of the Mobility Area correspond to the first four-month period of 2015. In this document, only the intensities corresponding to the east direction movement appear, being 15,877 vehicles/day in a workday, matching its peak time at 8.00 with 1,019 vehicles.

To analyse the latest data obtained from the average intensity of traffic in the west direction, the first four-month period of 2014 had to be checked, where the values obtained were as follows: The average daily intensity on working days was 825 vehicles, with a peak time at 21.00 and 133 vehicles.
Comparing both directions, there is a noticeable difference between the daily measured intensities, being much greater in the east direction (15,877 vehicles/day) versus the west direction (825 vehicles/day).

By using these data, it was considered, as a maximum instantaneous value, the following occupancy of vehicles inside the tunnel: 1 vehicle every 10 meters in each lane. This value as maximum occupancy is taken to obtain the maximum emission peaks and to work with legal admissible limit values. In this way, it is ensured that in case of lower traffic levels, these threshold limits are obviously achieved. It was checked in situ that, when the traffic lights of the surrounding streets are closed, and in peak traffic periods, these values are easily reached or even exceeded.

In order to model these sources, they are considered to be evenly distributed throughout the length of the tunnel, in staggered arrangement and in both directions.

The traffic noise spectrum has been obtained from Annex II of the NBE-CA88 [5], where this kind of emission is studied in depth. It is shown in the graph of Figure 3 that most of the emitted power is concentrated at low frequencies, particularly around 200 Hz.

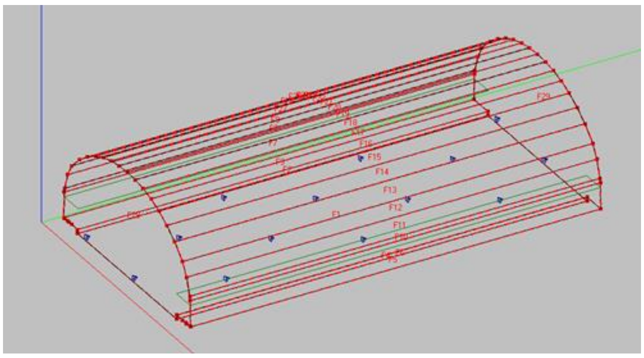


Figure 2 – Ease model of a section of the tunnel, showing the position of the sources.

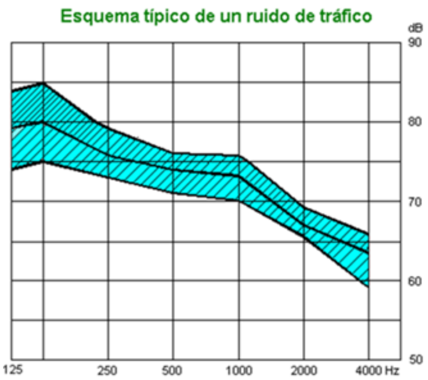


Figure 3 - Typical frequency spectrum of road traffic (SPL).

The noise spectrum illustrated in Figure 3 corresponds to measured SPL values at the edge of the road at a height of 1.20 meters. Both considering the SPL values and parameters (directivity *DI*, distance to the source *r* and atmospheric absorption coefficient α_{atm}), it is possible to estimate the source emission power PWL by means of Equation 1.

In Figure 4, the transmission power of each source is calculated, where SPL has been obtained from Figure 3, *r* = 1.845 m, *DI* = 3dB. The α parameter is calculated as a function of the frequency, considering Malaga usual meteorological conditions, i.e., temperature, humidity and pressure, concluding that is negligible for most of the cases.

$$SPL(r) = PWL - 20\cdot\log(r) + DI - 11 - \alpha_{atm}\cdot r \quad (1)$$

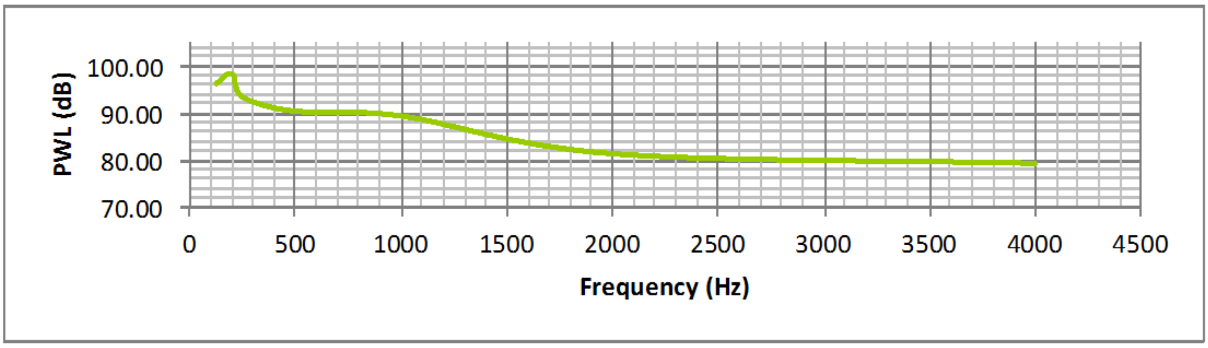


Figure 4 – Transmission power of a vehicle

Once the emitted power by the sources is known, it is introduced into Ease speakers, so that the emission curves are as similar as possible. Intermediate frequency values are approximated by linear interpolation.

After finishing the modelling of the enclosure and the sound sources, the sound levels are simulated on the areas determined as 'audience areas' in such place. It can be seen that the levels obtained, both direct and total, are very high, especially in the range of 200 Hz. The direct SPL level measured in the audience area is 98.45 dB. The total SPL levels reached, which are perceived by pedestrians, have a total average value with A weighted of 101.22 dBA.

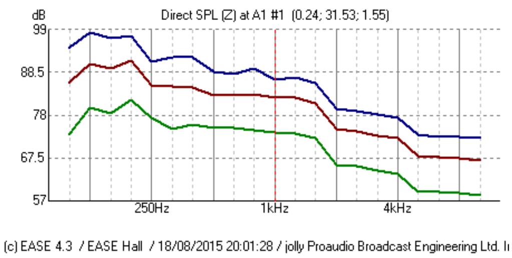


Figure 5 - Curve Direct SPL levels in the current situation.

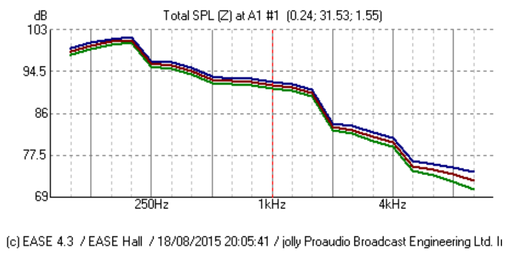


Figure 6 - Curve Total SPL levels in the current situation.

If these findings are compared with the data from the reports of noise level measurements made by the City of Malaga, it can be observed that the results agree with those obtained, obtaining an average value of 90 dB with peaks of 100 dB, which coincides with the model of the present study [6].

4 Mitigation noise alternatives

Considering the results above, it is verified the existence of a problem for pedestrian of excessive exposure to noise. In order to keep the pedestrian use inside the tunnel, some measures existing in the market to mitigate noise are studied to reduce the current exposure levels.

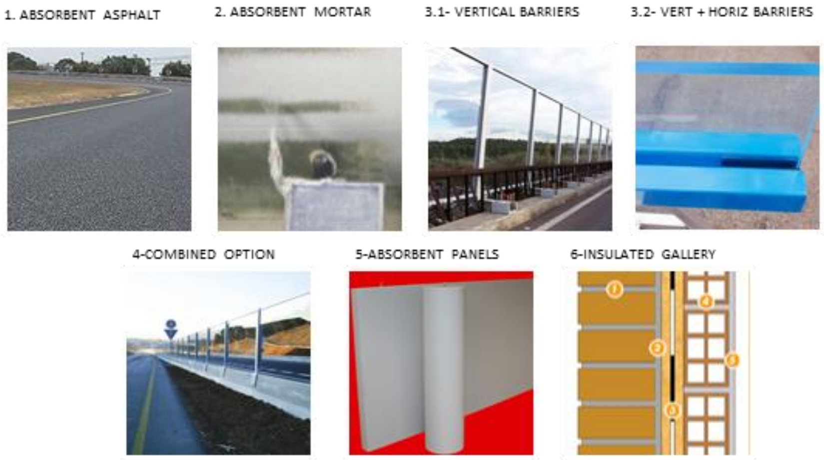


Figure 7 – Mitigation noise proposals.

The use of phono-absorbent asphalt is not well documented as it is a material made “in situ” and the acoustic characteristic are given by the granular structure of the used aggregate, the density of the mixture, the volume of bitumen and rubber employed, etc. However, as a rule, an average total noise reduction of 3 – 4 dB is estimated approximately, with a maximum of 6 dB. Its exclusive use, as it can be seen, does not solve the problem because the resulting levels are still excessively high.

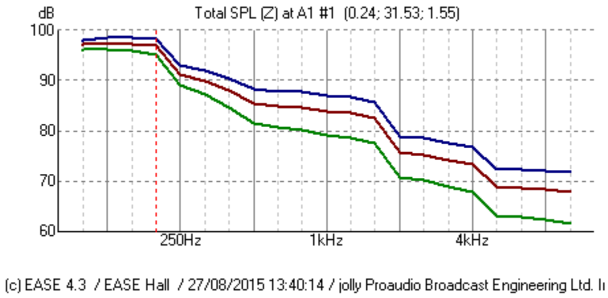
A reverberating problem of many reflections inside the tunnel by hard surfaces with very low absorption coefficient seems to be evident. Therefore, covering the interior face of the tunnel with a layer of projected absorbent mortar is considered as a possible measure.

These characteristics are modelled with the simulation program, obtaining the results shown in Figure 8.a in the audience areas.

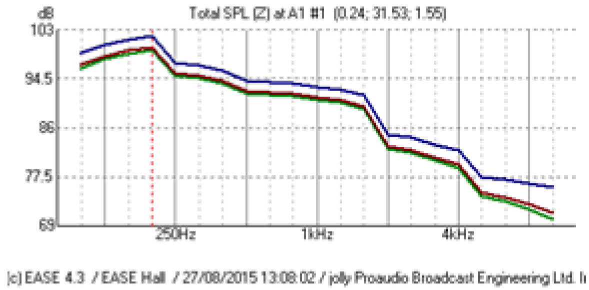
In this case, direct SPL levels are practically the same, as could be expected, while the total SPL levels have considerable decreases, with a total average value with A weighted of 94.45 dBA. This difference remains very low, so it is not enough as an implementing measure.

Another proposal arises by placing transparent noise barriers. In this category, methacrylate barriers are chosen because of its transparency, strength, ease of handling, heat resistance and noise attenuation rate (a typical value of R=30 dB is obtained with a 15 mm width barrier). Thus, apart from its function to reduce noise, being a transparent screen will have a lower social rejection for safety, cramped feelings or claustrophobic reasons.

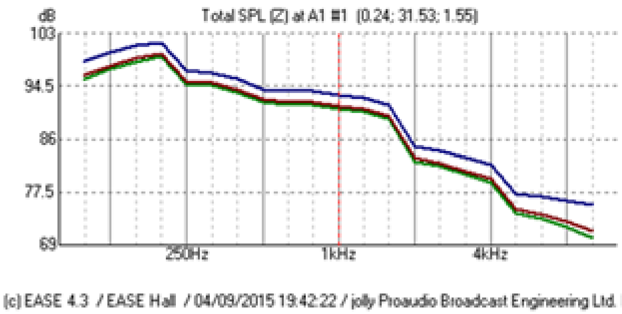
Two options are contemplated to place these barriers. The first one, only with vertical elements, and a second option, with vertical and horizontal elements. Both options try to avoid that the acoustic rays paths, caused by reflections into the geometry of the tunnel vault, reach the pedestrian area. The first option is simulated with a 2 meters high barrier, with the results shown in Figure 8.b.



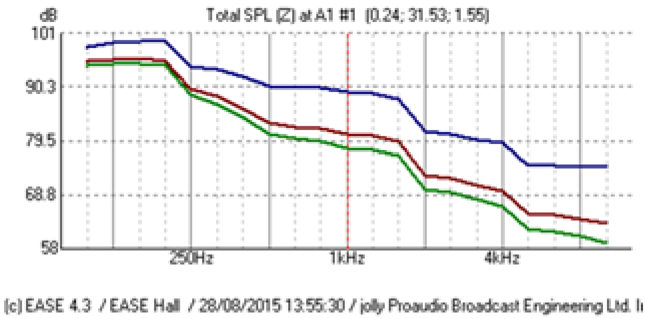
a)



b)



c)



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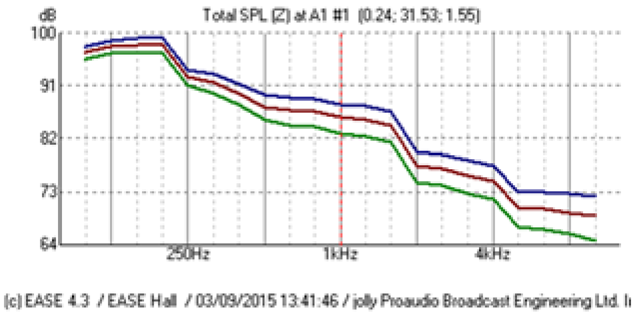


e)

Figure 8 – Total SPL results from each studied proposal. a) Projected absorbent mortar b) Acoustic barriers: option 1 c) Acoustic barriers: option 2 d) Combined proposal e) 5 meters panels.

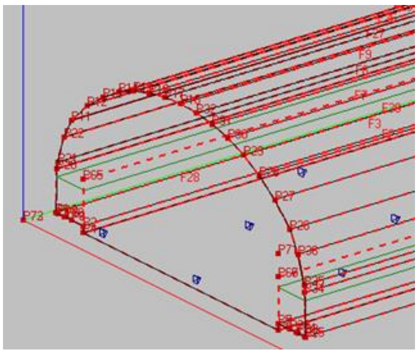


Figure 9 – Detail of barriers modelling in the simulation program.

It was found that the direct SPL is reduced drastically with this option, with a huge difference between maximum and minimum in the simulated levels, however, total SPL levels remain quite similar to the originals, with a total average value with A weighted of 100.5 dBA, that is, less than 1 dB difference, showing a problem of excessive reverberation.

In order to rule out the possible phenomena of early reflections in the pedestrian area, a horizontal barrier at 2.20 meters is considered, which coincides with the vertical one mentioned above. At this point, it must be said that a union between barriers has not been considered because a totally isolated enclosure should be ventilated, and an emergency evacuation should be provided. This assumption has been studied later with more common and cheaper materials. Once the planned barriers are inserted, the sound level is simulated in the scheduled audience areas.

It can be observed that large noise reductions are not achieved with these barriers. Direct SPL remains almost the same as option 1; however, there is a big difference between the maximum and minimum values. In Total SPL levels, no significant noise reduction is observed as it can be seen in figure 8.c.

Since each one of the individual measures does not solve the problem by itself, it has been considered the combination of the three of them. Thus, direct sound can be decreased by using barriers, while reverberated sound can be reduced with asphalt and absorbent mortar.

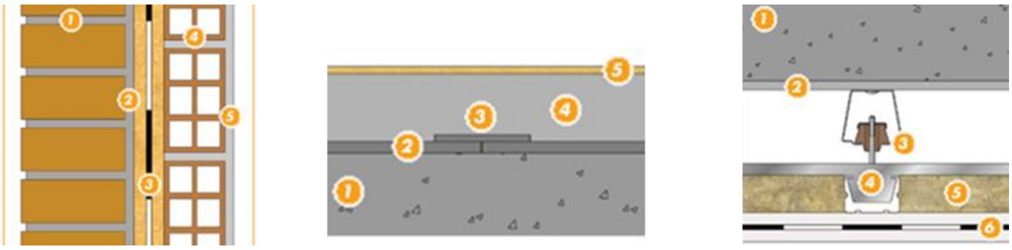
First, noise barriers and absorbent mortar are introduced in the model, with the results shown in Figure 8.d. In this case, a total A weighted value of 92.34 dBA is obtained. If 3 dB, the attenuation produced by absorbing asphalt, is subtracted from this total SPL value, we would have a total level of 89.34 dBA. Although this value experiments a significant reduction, it remains too high, besides the high cost of the implementation of the three measures.

Placing absorbent panels instead of using a mortar layer is analized to increase the absorption of the enclosure. Three different panel configurations are studied: the first with a line that begins at 2 meters high until 4 meters high, the second begins at the same point but reaching 5 meters high and, finally, the last configuration goes from the ground to 5 meters high. All the options are simulated and the greatest reduction is obtained in the third option, although the result is not particularly high as it can be seen in Figure 8.e, since it is only reduced a value of 5 dB.

The latest proposal is perhaps the one which most modifies the internal geometry of the tunnel because it is planned to unify the sidewalks, moving lanes, and to place an insulating wall to separate vehicles and pedestrians spaces. In order to configure the desired interior noise level, established acoustic quality limits have been consulted in the spanish legislation. In this study, it has been considered that the use of this passage at night is minimal, both for pedestrians and for existing traffic inside the tunnel; therefore, the calculation is made only for daytime being this the worst possible scenario. Note that the maximum peak of average daily traffic is in daytime. If the enclosure is going to be assimilated to a cultural urban space, which will be described later, the quality objective [7] [8] stipulates that the maximum contaminant traffic noise should not exceed 60 dB inside the tunnel.

To adapt the proposed level to human ear perception, NC curves are used. In this case, an interior level between 50 and 60 dB must be reached, which corresponds to NC45 curve. Knowing the existing noise in the outside area and the inside desired sound level, the required insulation for the dividing wall can be calculated. Operating according to the established procedure in ISO 717-1:2013 [9] and EN 12354-1:2000[10], a requirement standardized global insulation of 50 dB is obtained.

The solution for the insulating wall is to provide a multiple layer one composed of a standard 12 cm width brick wall, a plaster trim and a multilayer insulation compounded of a bituminous sheet with porous material on both sides. The whole is coated with a double hollow brick partition and plaster interior trim. To avoid transmissions, a 10mm impact noise insulating layer on the slab made of cross-linked and foamed polyethylene is contemplated. After that, a slightly reinforced protection mortar is poured over this set, and it will end with a decorative finish. The upper horizontal partition is treated with a suspended ceiling which consists of a welded steel structure where the shock absorbers will be fixed to hold the ceiling profiles. Under this, a 40 mm mineral wool layer and an acoustic sandwich panel formed of two plasterboard sheets with an inner acoustic membrane are arranged.



a) b) c)

Figure 10 - Acoustic insulation a) Designed wall section b) Designed floating floor section c) Designed suspended ceiling section. Source: http://www.danosa.com/.

In order to avoid the stifling hall effect, some windows have been planned, which connect the study area to the vehicle space, and two doors for emergency evacuation. These elements, to prevent an insulation weakening in the wall, must have special acoustic characteristics.

Knowing the dimension of all gaps to install and the insulating wall, the calculation equation for mixed insulation [11] can be used, obtaining a global insulation of 51 dB, which is higher than the previous calculated limit of 50 dB.

$$R = 10\log\left(\frac{Sv + Sp + Sc}{Sv \cdot 10^{-0.1Rv} + Sp \cdot 10^{-0.1Rp} + Sc \cdot 10^{-0.1Rc}}\right) \quad (2)$$

Where:

R is the global mixed reduction index. (dB)

Sv, Sp, Sc are the surface to windows, doors and the wall respectively. (m^2)

Rv, Rp, Rc are the acoustic reduction index corresponding to windows, doors and the wall respectively. (dB)

The created corridor forms a public gathering space that will have to be equipped with all facilities of safety and comfort which are demanded by different regulations and codes (fire protection, emergency evacuation, ventilation, electrical safety, etc.).

Furthermore, Malaga is emerging as a city that supports a very important cultural selection. In this context, it is considered that in the existing supply will fit a gallery for the “Alternative Art” or “Underground”. This created space inside the passage is ideal for showing this type of art, since its appearance perfectly fits with the “Underground” urban art and does not requires an excessive acoustic conditioning. Spaces with glass boxes have been planned for the most valuable works and the opposite area could be dedicated to the graffiti art. The existent hall can incorporate a bike lane, which is perfectly compatible with the idea of the exhibition gallery indicated above. All this will define a whole idea that could become a centre of attraction for all those who want to enjoy a different perception of art.

The above clashes with the useful width of the corridor because it can be too narrow. However, these dimensions could be considerably increased if one of the lanes of the tunnel is eliminated. Note that, according to provided statistics by the Mobility Area of the City Council of Malaga, the daily measured intensity in west direction is quite small. In addition to this value, the effect of the possible pedestrianization of surrounding streets must be added.

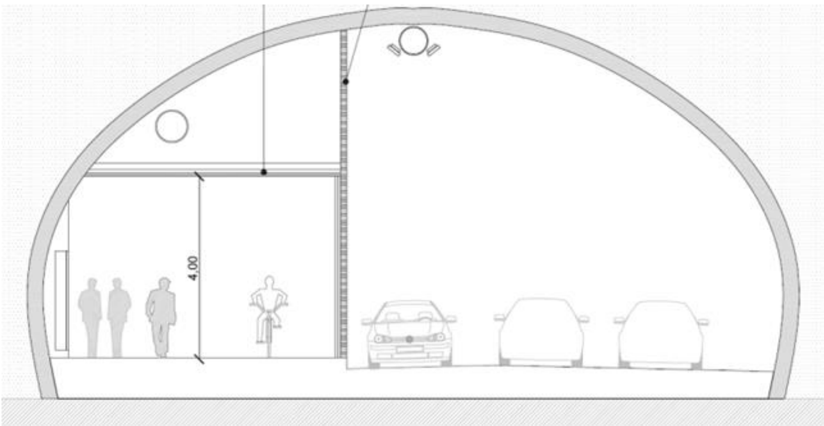


Figure 11 - Section of the proposed gallery with a suppressed lane

Figure 12 - Interior elevation of the proposed gallery

5 Results

Shown in the table below, a summary of the obtained results can be seen, indicating the noise reduction for each solution and the final achieved levels

Table 1 – Summary of improvement proposals

PROPOSAL	DESCRIPTION	ACOUSTIC REDUCTION (dBA)	FINAL SOUND LEVEL (dBA)	COMPLIANCE WITH OBJECTIVES
1	PHONO-ABSORBENT ASPHALT	3	98,22	NO
2	ACOUSTIC MORTAR	7	94,45	NO
3	METHACRYLATE BARRIERS	1	100,5	NO
4	ASPHALT+MORTAR+BARRIERS	12	89,34	NO
5	ABSORBENT PANELS	5	96,18	NO
6	INSULATED HALL	41	60	YES

6 Conclusions

In conclusion, certainly the most advisable option to solve the existing problems in the tunnel is the construction of the insulated gallery, which has a number of advantages. It is the only one that meets the acoustic quality objectives, it does not imply an additional load to the tunnel structure, it allows the existence of a bike lane and therefore encourages a reduction of traffic and a reduction of pollutant emissions, it creates an indoor pollution-free environment, with controlled ventilation and lighting, for pedestrians who go through the tunnel, and it allows the use of this space to provide a gallery of Underground Art.

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