

Life cycle analysis of mitigation methodologies for railway rolling noise and groundbourne vibration

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LIFE CYCLE ANALYSIS OF RAILWAY NOISE AND VIBRATION MITIGATION METHODOLOGIES

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ABSTRACT

The advance of Railway Industry in the last years has motivated many countries to adopt this mode of transport over others, such as roads, because its facilities in time and overall cost. However, some bad outcomes such as noise and vibration generated by railways has become a challenge for both industry and academic in order to guarantee that the system can accomplish its purposes and at the same time provides comfort for users and living people at the surround areas. The interest on this field has becoming higher and advances in mitigation methodologies and researches can be observed on different technology that are constantly put into test to solve such effects.

The life cycle analysis of mitigation measures consists in detailing the efficiency of certain types of mechanisms of control on Rolling Noise and Ground Vibration. The research is based on the materials used, the total cost assumed to maintain the measure and the carbon footprint left for each type of mechanism. This last parameter can be decisive for the industry in the selection of mechanism since environmental is a growing concern in the world. In addition, the life cycle analysis gives a general view of the measure considering a certain period from when the measure is adopted until renovations are necessary. The typical value for a life cycle of railway systems is of 50 year, and this is the period considered for the cash flow. All the estimations are assuming a 100km length track in an urban area, with high density of people, therefore, with very strict limits for noise and vibration.

KEY WORDS: Railway Noise, Railway Vibration, Rolling Noise Vibration, Ground Vibration, Life Cycle Analysis, Environmental Impact.

1. Introduction

The greatest challenge of Railway Noise and Vibration mitigation methodologies is the effectiveness compared to the effort needed to place them. The first thing that needs to be taken in consideration is the physics behind such phenomena (Appendix 1), depending on the type of noise and vibration generated there is a physical difficulty to control the waves which would require mechanisms of control that are impractical to be built. In addition, railway systems usually extend for many kilometres and these implementations are often expensive to be built along all the track line, there must be a comparison between their effectiveness and need for maintenance to the cost necessary for the industry to the implementation of such solutions. The type of mitigation methodology relies on the source of noise and vibration that is being analysed; however, the perception of noise is derivate from an interaction between different sections of the track (Appendix 2).

The major source studied is the wheel/rail interface that generates troubles such as rolling noise, impact noise, curve squeal and changes in the track like in super elevations and special track work. The amount of noise generated by this source is highly connected with other problems that the track may present such as track degradation, changes in bridges, loss and pulverization on ballast creating poor settlement, and others. The contact of wheel/rail has been studied and evolved over the years to create a support that can withstand the dynamic forces imposed and at the same time reduce the friction that is the major responsible for generating such disturbances. With this stated, the mechanism of control of this source consists on geometry of wheel and rail with support of other systems such as noise barriers and rail dampers that are going to be analysed in this work.

The second major source of disturbance that is going to be analysed by its mitigation measures is the ground. The constant impact between the rail system and the ground produces a great amount of energy that dissipates from the rail area and affects the surrounding areas of the track in the form of vibration, which can compromise the

living people around and the constructions that may collapse under such disturbances. The amount of vibration depends on many factors such as the constituent materials of substructure of the railway and their ability to absorb impacts and constitutes the hardest to control due its physical properties.

2. Rolling Noise and its mitigation measures

2.1. Introduction to Rolling Noise

The measurement of noise on track is usually made by placing microphones in a certain distance of the track in order to capture the sound pressure and its sources. The most notorious source it is the rolling noise. When the train approaches the microphone there is a gradual increase in the sound and a same gradual decrease after the whole train has passed the points of passage. It is important to notice that the sound increases when the bogies passes, indicating the importance of the wheels. The result is a high frequency vibration that is transmitted to the structure of the track creating new sources of vibration and to the air.

The impact on terms of noise and vibration generated by Rolling Noise is the one that brings greater problems to Railway Industry because it generates the higher pressures. Some factors have a high impact on the level of the sound and vibration, such as:

- **Speed:** there is an increase in the sound pressure in higher velocities, which can be a real concern when dealing with High Speed Trains.
- **Constituent materials and design:** the constituent materials, especially at the wheel and rail interface; the design of components and their area of contact; and how the load distribution to the substructure happens is significant to the final noise produced.
- **Conditions of track:** the lack of maintenance of railway systems leads to deterioration and corrosion of the components. These outcomes increase the roughness of the track that increase the sound pressure level.
- **Weather:** there is not a direct relation between the weather conditions and the rolling noise, but the occurrence of floods in the track can lead to flanging noise due oxidation of the track.

2.2. Life Cycle Analysis of Mitigation Measures

For being the source most studied in terms of noise and vibration outcomes, there are several methods studied to reduce those disturbances. The most common methodologies that are going to be analysed are:

- Reduction of Roughness
- Noise Barriers
- Structure modifications and damping system

2.2.1. Reduction of Roughness

A regular and smooth rail is an important element in reducing railway noise. There are many techniques to maintain the regularity of the rails and they consist on removing corrugated layers of the rails. Rail lubrication is the most known measure to maintain the low friction and the use of products like this are vital not only to reduce the noise produced but also to keep good conditions of track.

The use of lubricant must be done carefully: creating a surface that reduces the roughness of the surface but at the same time avoids the derailment. There are many different products available in the market using different chemical compounds and the products with lower pollutant emission are preferable in order to reduce the final carbon footprint of this measure. The use of lubricants is common for track maintenance, and compared to rail-wheel life improvement and the noise reduction it offers its costs are relatively low.

Table 1: Reduction of Wheel maintenance due lubrication (Larke 2003 and Reddy et al. 2006)

Track/vehicle condition	Wheel Life in (km)	Wheel Life in (week)	Annual wheel cost in (£)
No lubrication	170,000	20	1.6 million
Rail lubrication	300,000	35	825,000
Vehicle lubrication	1,000,000	118	250,000

The regular grinding of railways is also an essential part of good track maintenance. The grinding is responsible for the removal of corrugated layer and it is a regular activity that extends the life of the track, being cost saving as track defects and safety issues decrease. ‘Acoustic grinding’ implies that an additional grinding is executed dedicating only to noise reduction of rolling. This additional grinding improves the smoothness and helps in noise reduction.

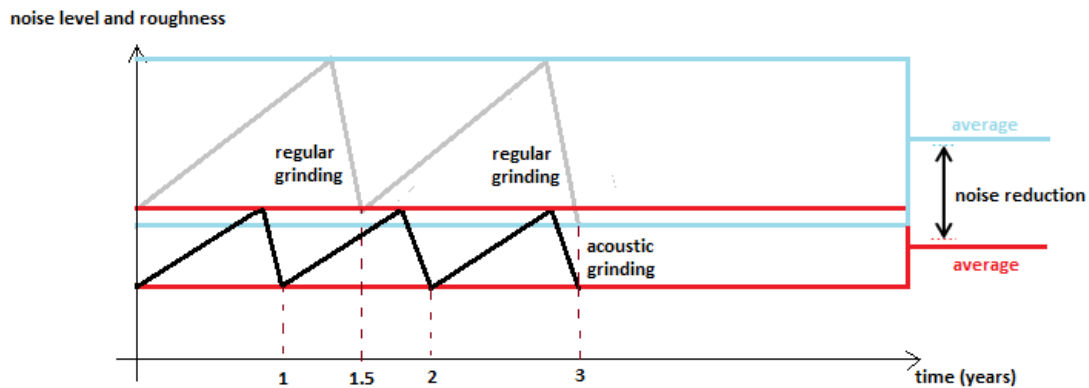


Figure 1: Effect of acoustic grinding compared to regular grinding

Table 2: Cost Assumptions for life cycle analysis of reduction of roughness mitigation measures

Mitigation measures	Assumptions
Wheel/Rail lubrication	£10,000 per km lubricated
- Control case	Maintenance every 3 months
- Adverse climates	£1,800 total cost per year per km in hot weather
- Carbon Footprint	Between 7.03 and 7.75 kg of CO2 produced by each kg of lubricant (PTFE)
Acoustic Grinding	£6,400 per km of grinding
- Control case	Acoustic Grinding one time per year
- Adverse climates	£8,200 per km of grinding
- Carbon Footprint	Around 1.52 kg of CO2 produced by each kilometre of grinding

2.2.2. Noise Barriers

A noise barrier reduces the sound level of receiver by braking the direct line of sound and obligating the noise to diffract with a solid wall. The barrier creates a noise shadow with less energy because of the diffraction. The attenuation of noise barriers are usually between 5 and 15 decibels depending on the height, length, and distance from the track.

Placing the barrier closer to the track can be an alternative for the conventional barrier. Normal barriers are placed in a distance of 4 meters and have between 1 and 4 meters of height. Closer barriers are installed around 1.70m of the track and have the main advantage of reduced height, which reduces the cost of material and does not block the view of trains making them more acceptable in urban designs.

In a point of acoustic view, barriers closer to the track may be more effective than standard distances. However, in a construct and maintenance there might be some problems with this approach, for example: conflict with track drainage, cables; track maintenance can be more difficult; risk of snow building up in barriers; and finally, the cost can be similar with normal height barriers if there is a necessity to place barriers between tracks.

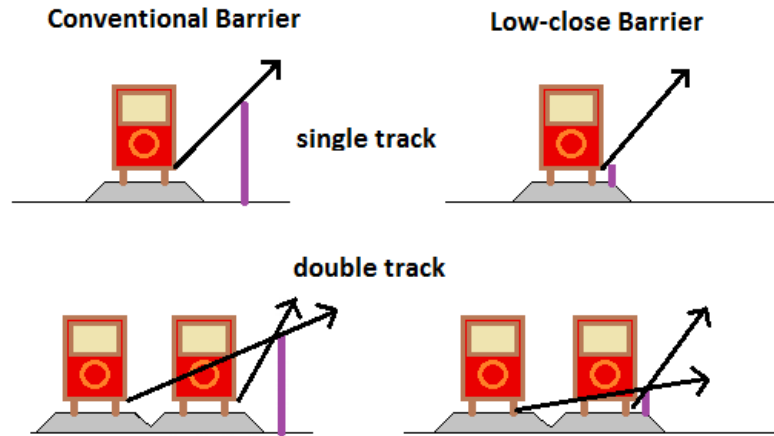


Figure 2: Conventional and Low-Close barrier effects in single track and double track

Table 3: Cost Assumptions for life cycle analysis of noise barriers

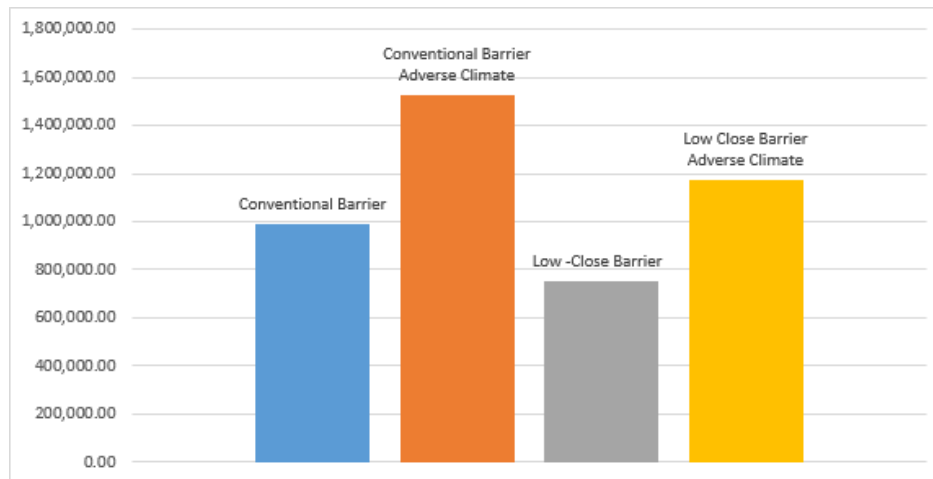


Table 4: Comparison with adverse climates for the two different types of noise barriers

Mitigation measures	Assumptions
Conventional Barrier	Initial cost of £820,000 per km with 50 years of life
- Control case	Replacement in 25 years
- Adverse climates	In adverse environment there is a need for replacement in 12 years
- Carbon Footprint	Between 0.116 and 0.128 kg of CO2 emission per kg produced
Low Close Barrier	Initial cost of £550,000 per km with 50 years of life
- Control case	Replacement in 20 years
- Adverse climates	In adverse environment there is a need for replacement in 10 years
- Carbon Footprint	Between 0.116 and 0.128 kg of CO2 emission per kg produced

The outcome of the analysis shows that the conventional barrier is going to be more expensive by the end of the life cycle, since the cost for maintenance is low compared to the initial cost of the method. In case of single track, the low close barrier has a lower cost with the same reduction of noise. However, if the system is more complex with lots of tracks, the additional cost of conventional barriers is necessary to provide a good reduction on the noise. The constituent material of the noise barrier is the high-density concrete, which provides better noise isolation and is the one used to obtain the CO2 footprint of the mitigation methodology.

2.2.3. Structure Modifications and Damping Systems

Structure modifications do not consist as mitigation methodology of noise reduction, and for this reason the life cycle analysis is not possible. However, it is important to outline that during the process of design of the structures of the track, designers should pay attention on the shape given, especially for wheels and rail. These simple modifications on the structure can result in a huge decrease in the noise level of the track. The cross section of wheels can have a huge influence on the noise radiated, especially about the shape of web and the wheel diameter.

In addition, the damping system must be effective not only to contain the dynamic forces imposed in the structures but also to reduce the noise promoted by the trains. The problem with damping rail is that rails are already highly damped system, but these dampers must have the necessary isolation to achieve significant noise reductions.

2.3. Conclusions on Rolling Noise Methodologies

The methodologies analysed for reduction on the rolling noise presented result in a revision of the principal methodologies used by track maintainers. It is hard to make a good comparison in the final life cycle since some of the methodologies require annual usage like rail lubrication while others are a one-time expenditure with small maintenance cost like noise barriers.

Considering the life cycle showed, the comparison between money spent and environment impact is an important matter to consider by the industry. In the carbon footprint analysis consisted on the production of the material used and, in the case of the grinding, the emission of the CO₂ by the machine. With this stated the approach showed different units of measurement: kg of CO₂ by kg of material produced and kg of CO₂ by km grinded. To enable a comparison of cost and environment impact, the consideration of the 100 km length track was used:

Table 5: Comparison between CO₂ emission and price in the Rolling Noise and Vibration Mitigation Measures

Environment Analysis - Rolling Noise Impact					
Methodologie	kg of material/100km	reference kg of CO ₂ by km or kg	Total kg of CO ₂	Cost	Cost Adverse Climate
Acoustic Grinding	-	1.52	152	123,237.92	157,898.59
Lubrication	3.7	5.31	19.647	42,860.67	61,116.59
Conventional Barrier	73500000	0.119	8746500	1,062,148.27	1,751,277.98
Low-close Barrier	24500000	0.119	2915500	835,414.34	1,348,286.28

In terms of life cycle analysis and environment aspect, the noise barriers constitute a methodology with a high carbon footprint involved in high prices involved, especially because of the amount of material used. The lubrication and grinding have lower price, but the grinding presents also a reduced emission. Based on this comparison, the best methodology is the acoustic grinding, however, the efficiency and practicality of the method must be considered in the choice of method applied.

3. Ground Vibration and its mitigation measures

3.1.Introduction to Ground Vibration

The effect generated on the ground is different from the one in the rolling system of the track. While the former can be perceived as both noise and vibration, the ground propagation is more perceived in terms of vibration. This effect of this vibration includes a perceivable movement of the building floors, rattling of windows, shaking of items, etc. In extreme cases, the vibration can cause deterioration to the surroundings and it is a constant disturbance for living areas near by the track. The assessment of vibration result in an analogy of noise effect, determining the total effect of the surrounding living areas within a period.

The vibration propagated by ground can be in low frequencies in the case of surface propagation or, in the case of ground borne, in high frequencies. The energy transmitted depends on the properties of damping system, materials used and how the force is distributed along the structure. The human response to vibration is influenced by the acceleration of the waves and it is important to outline that the perception of noise and vibration is higher indoors, where the building is highly affected by the increase of energy.

3.2. Life Cycle Analysis of Mitigation Measures

The principle used for mitigate high frequencies vibrations from the ground is to isolate the vibration of the rail from the ground, especially the resonance frequency generated by the wheel/rail interface. In modern railway track, the use of slab track has grown due its lower maintenance and higher stability. However, the slab track generally lead to higher levels of ground borne vibration. The most common methodologies to reduce the vibration in slab tracks involve modifications on the structure such as the use of booted sleepers and floating slab track. The mechanism of control analysed for ground borne is going to be the use of sleeper soffit and ballast mats.

For the low frequencies vibration generated in the surface, there are no generally mitigation methodologies applicable. This occurs to the long wavelengths of vibration of track and ground, which can only be controlled with large-scale civil engineering measures. Therefore, the amount of money and effort necessary versus the reduction perceived demotivate the constructors to invest in this type of technology. The main mitigation methodologies studied in this paper are:

- Sleeper and ballast mats
- Trenches and buried walls
- Wave-impeding blocks

3.2.1 Sleeper soffit and ballast mats

Sleeper soffit and ballast mats are put under the named structures to lower the stiffness and therefore the track resonance frequency:

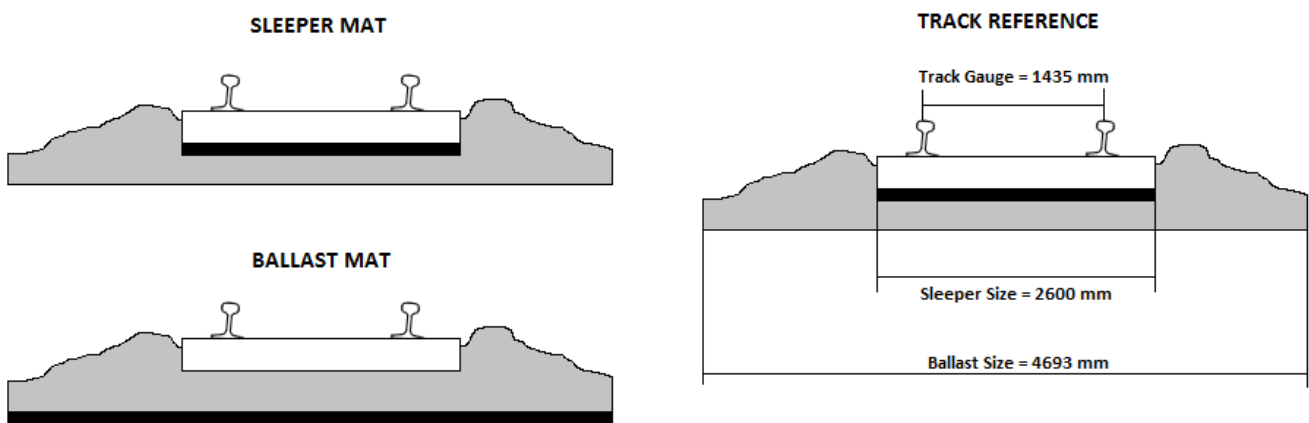


Figure 3: Sleeper and Ballast Mat

The use of ballast mats can restrain both slab tracks and ballasted tracks. The characteristics of the material must be able to provide the necessary stability for the track, not too soft to compromise the train passage and hold the vibrations. Sleeper soffit pads have the advantage that they are simple to install during a resleeping operation, since they are delivered already fixe d to the bottom of the sleeper (Thompson; Jones Gautier, 2009).

The material used for the analysis is the natural rubber elastomer and the differences of the mat are the dimensions. Because the area of ballast mat is a lot greater compared with the sleeper, there is a significant difference in the costs of both methodologies. However, the stability and the noise reduction provided by ballast mat is superior and it is a technology more used, resulting in less changes of mistakes.

Table 6: Cost Assumptions for life cycle analysis of Sleeper and Ballast Mat

Mitigation measures	Assumptions
Sleeper Mat	£ 1,357,200.0 initial cost
- Control case	£800 cost per month and maintenance every 25 years
- Adverse climates	£1,300 cost per month and maintenance every 15 years
- Carbon Footprint	Between 1.86 and 2.05 kg of CO ₂ by each kg of natural rubber produced
Ballast Mat	£3,037,685.4 initial cost
- Control case	£1,200 cost per month and maintenance every 25 years
- Adverse climates	£2,100 cost per month and maintenance every 15 years
- Carbon Footprint	Between 1.86 and 2.05 kg of CO ₂ by each kg of natural rubber produced

3.2.2 Trenched and buried walls

The use of trenches and buried walls are a great mechanism to attenuate the vibrations generated by the track. To achieve high attenuations of vibration it is necessary to build impractical depths of trench. For practical purposes, the depth of 4 meters was adopted and it can decrease in half the height of the wavelength. The costs for the methodology include, in both cases, the excavation along the track. For the trenches is necessary to side the excavation to avoid soil loosening, while in the buried wall the trench is filled with jetted concrete.

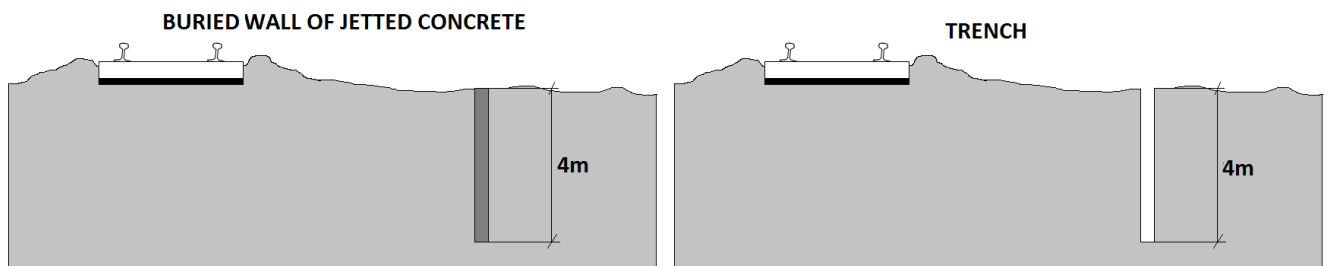


Figure 4: Scheme of buried wall and trench

Table 7: Cost Assumptions for life cycle analysis of Trenches and Buried Walls

Mitigation measures	Assumptions
Trenches	£ 1,245,626.70 initial cost
- Control case	£1,100 cost per month and maintenance every 25 years
- Adverse climates	£1,700 cost per month and maintenance every 15 years
- Carbon Footprint	No substantial value
Buried Walls	£2,600,626.00 initial cost
- Control case	£700 cost per month and maintenance every 25 years
- Adverse climates	£1,100 cost per month and maintenance every 15 years
- Carbon Footprint	Between 1.86 and 2.05 kg of CO ₂ by each kg of natural rubber produced

By the assumptions of each methodology, the final cost of buried walls is almost twice as the trench and the carbon footprint show expressive values. However, the isolation promoted by the walls is a lot greater and the annual maintenance is inferior since the concrete gives protection to the soil and avoid erosion.

3.2.3 Wave-impeding blocks

In some locations, the construction of trenches and buried walls is impossible due existing assets around the railway track. For this instance, the wave-impeding block is a methodology where the soil under or close to the track is stiffen to modify the ground layer structure. This way, the modal propagation regime changes and there is a vibration reduction at low frequencies.

As the methodology consists uniquely in stiffen the soil, the cost generated is only with the machinery used to compact and the CO2 footprint is so low that can be disregard at the life cycle analysis.

Table 8: Cost Assumptions for life cycle analysis of Wave-impeding blocks

Mitigation measures	Assumptions
Wave-impeding blocks	£1,028,000 initial cost
- Control case	£1,100 cost per month and maintenance every 25 years
- Adverse climates	£1,700 cost per month and maintenance every 15 years
- Carbon Footprint	No substantial value

3.4. Conclusions on Rolling Noise Methodologies

The methodologies used to control the ground vibration have the great advantage that some of them consists only in mechanisms that do not contribute to the CO2 footprint of the railway system. As it is shown in Table 9, the cost of the methodologies with no footprint are also the cheapest. However, because the use of trenches and wave-impeding blocks do not involve new materials, the isolation of noise and vibration is not as effective as the buried walls and mat provides.

With this stated, in vibrations and noises that do not cause large disturbances, the use of trenches and wave-impeding blocks can be enough to control. However, in systems where the disturbances reaches higher values, the use of mats and buried walls represent a better solution even with the emission and higher cost.

Table 9: Comparison between CO2 emission and price in the Ground Noise and Vibration Mitigation Measures

Environment Analysis -Ground Impact					
Methodologie	kg of material/100k m	reference kg of CO2 by kg	Total kg of CO2	Cost	Cost Adverse Climate
Sleeper Mat	4,888,000.00	1.86	9,091,680.00	1,772,353.42	2,497,775.41
Ballast Mat	8,822,840.00	1.86	16,410,482.40	3,956,275.07	5,576,407.39
Trench	-	-	-	1,633,220.44	2,162,828.43
Burried Walls	98,000,000.00	0.12	11,368,000.00	3,381,170.50	4,472,595.66
Wave-impeding blocks	-	-	-	1,351,327.93	1,790,165.60

4. Conclusion

In Railway Industry, the larger parcel of investment is driven to maintenance of the system, which is very valuable to the noise and vibration: once the track is in good conditions, there is significant reduction on these outcomes. However, in many systems there is a necessity to create new methodologies to have a better reduction in noise and vibration. During this work, some of those methodologies were analysed by its life cycle, which is a good parameter of evaluating the available technology in the industry and can be for great use to choose the best solution for the vibration and noise outcomes.

The life cycle consists on analysing the cost and environmental impact generated by different methodology of reduction in noise and vibration of rolling noise and ground. The cost matter usually is the one that caught more attention of companies; however, more recently the necessity to reduce the CO2 carbon footprint has become a great issue. It is important to outstand that the life cycle does not evaluate the efficiency of the mechanism, but with the methodology procedure and materials involved, the notion of efficiency can be constructed.

In the rolling noise, the methodologies that constitute a better solution are the lubrication and the acoustic grinding. Both have reduced costs when compared with the noise barriers and the acoustic grinding have the great advantage of being a solution with low carbon footprint. In addition, lubricants used in maintenance and there is a great variety of products available in the market, being therefore, a well-known technology. The use of noise barriers provide a better reduction than the acoustic grinding and the lubricants, because it constitutes in a barrier of concrete that have a great impact. The best use of this methodology is to build noise barriers in extreme cases of noise and vibration where there are many people nearby the track. This way, the reduction in noise and vibration is provided and the costs and CO2 emission is not elevated since they will be present in few lengths of the track.

For the ground disturbance, we have the same outcome, the methodologies that represent the lower costs and CO2 impact, which are trenches and wave-impeding blocks are the ones who constitute lower efficiency. Therefore, the use of mats and buried walls can be used like the noise barriers, only in certain places with high density of people and great values of noise.

With this work, we can conclude that the life cycle analysis constitute in a great mechanism of evaluation of systems and it is a good way to create a panorama of all the technology available. However, with all the results and efficiency analysis, the best choice of methodology must be coherent, in a way that the reduction reaches reasonable values for the people inside the train and by the track, and the costs are not extreme along with a preservation of the environment.

APPENDIX

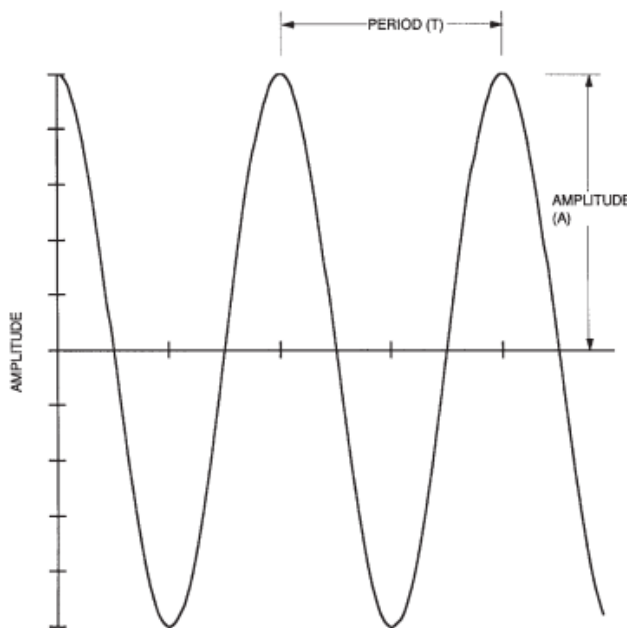
APPENDIX 1: Noise, Vibration, and its measurements parameters

To evaluate the effectiveness of a methodology that control noise and vibration of track areas it is necessary first to understand what is the phenomena of noise and vibration, what are the main properties and how they behave due different sources and aspects. This appendix is dedicated to give a brief explanation about the basic understand of noise and vibration, how it is measured and how it is contemplated by different standards in terms of tolerable outcome.

Noise and Vibration are undesirable outcomes propagated by natural or artificial sources. In a more physic perspective, the noise is a disturbance of the atmospheric air and it propagates in form of small waves. The vibration and noise propagates due the disturbance of air molecules around the source and its properties depends on many factors that are presented below. The properties of the vibration are crucial do determine the effectiveness of mitigation methodologies and their life expectancy and should be always considered since each type of source has its own characteristics. The general properties to classify the sound are:

- a) Frequency and Wavelength: the frequency is the measure of the number of cycles that happen in one second. It is closely related to the wavelength (defined in the equation below) and the pitch of the noise.

Figure 1: Period and Frequency



$$f = \frac{1}{T} \text{ Hz}$$

Formula 1: Frequency and Period

Where f is the frequency determined in Hz (Hertz) and T is the wavelength or Period, which is the time between each cycle. The frequency is the most important parameter when dealing with control of noise, because of the phenomenon of **diffraction**. This phenomenon guarantees that the sound as also the other types of waves, have the property of surround obstacles imposed between their sources and keep travelling. If the sound is a low-pitch noise, for example, it has a long wavelength which means it can deviate from almost any

obstacle and to be controlled it would require barriers with dimensions that are almost impossible to be built. In the other hand, noises with high pitch have smaller lengths and can be easily controlled, which brings more facility to proposed mitigation methodologies.

- b) Amplitude: Also known as, the height of the wave, as shown in the Picture 1 determines how strong the noise will be. If the amplitude of the wave produced is very high it will generate a strong noise that may cause damage to people in the surrounding areas or inside the train.
- c) Perception of sound and Sound Pressure Level: The perception of the noise is related to many aspects of the wave such as the pitch, the duration, the loudness and the timbre. Those aspects are related to the characteristics contemplated and it is how the human perceive the noise by the different aspects. The Sound Pressure Level is one of the most important parameters of evaluation of the noise, since it compares the pressure of the atmospheric with the pressure generated by the noise. The unit used for this measurement is the Decibel (dB) and it is used by standards to regulate the permissible noise around track areas. The equations used to determine the Sound Pressure Level and the relation between the distance from the source and the level of sound are expressed by the following expressions :

$$Lp = 20 \log_{10} \frac{p}{p_{ref}} \text{ dB}$$

Formula 2: Sound Pressure determination for a given pressure level

Where Lp is the sound pressure and p_{ref} is the reference pressure sound, in this case, the air pressure and p is the pressure of the sound produced. However, because the analysis of this work consists in the movement of train, there is a variation of noise level before the passage of the train and after it, the encounter with a special trackwork or even in a curve. To measure the sound pressure variation, it is used the Leq which it is the continuous noise level that follows the fluctuations of noise along time.

In the UK the permissible continuous noise level depends on the density of population in the surrounding areas of the track. The Noise Action Plan: Railways (Including Major Railways) -Environmental Noise (England) Regulations 2006 determine that:

Figure 2: England Regulation for noise

Noise Level (L_{den}) (dB)	Number of People
≥ 55	375,000
≥ 60	211,000
≥ 65	106,000
≥ 70	44,000
≥ 75	11,000

APPENDIX 2: The Sources

It is important firstly to outline that the noise generated by rolling noise constitutes in a sum of factors from different components of the track: the wheel, the rail and the sleepers and how the interaction between these components happen. Since there are different sources that interact between each other, the reduction of noise in one of the components not necessarily is going to result in an overall expressive reduction and this is explained in the expression below. Considering two sources disconnected that produce two different sound pressures $L1$ and $L2$ at the receiver location. (D.J. Thompson, 2008) gives the combined sound level:

$$L_{total} = 10 \log_{10} (10^{\frac{L1}{10}} + 10^{\frac{L2}{10}})$$

Formula 1: Total sound pressure from two different sources

This expression shows that if there is, for example, a willing to control the noise level of wheel and rail interface must be done with measures that act in both sources. Assuming that both sources produce the same initial sound pressure, if there is a reduction in 10dB in any of the sources, the total reduction will be of only 2.6 dB. However, it is likely that a modification in one of the sources of rolling stock should influence in modifications on the other related sources as it is going to be analysed in sequence. The rolling components analysed and mitigation methods that are going to be analysed in this paper follow the system proposed by the Railway Noise and Vibration of D.J. Thompson:

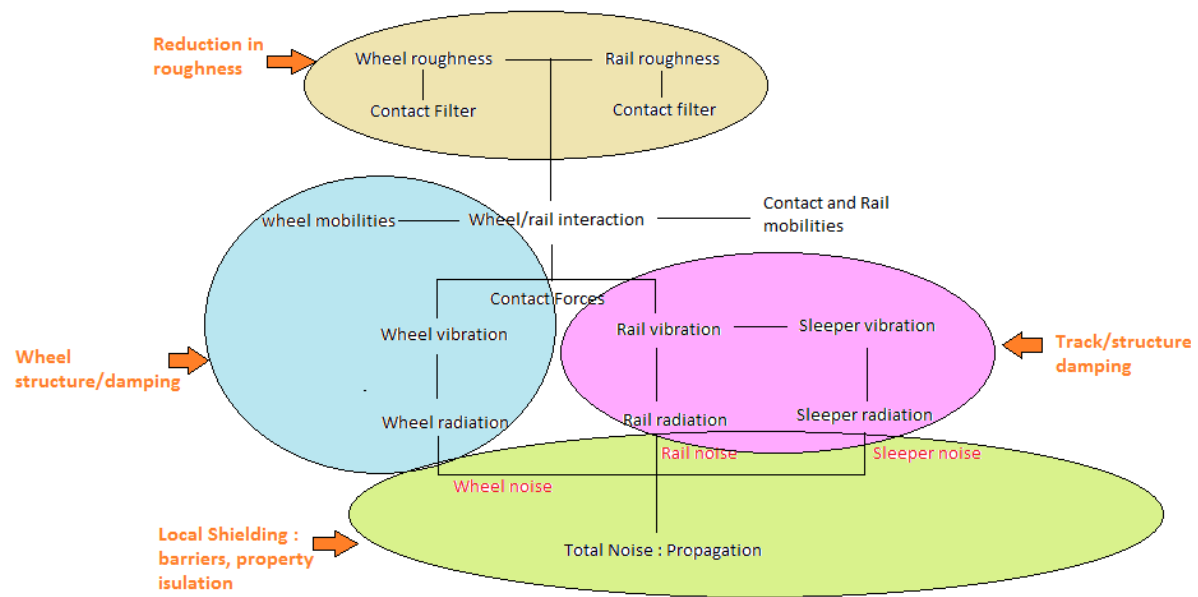


Figure 1: Scheme of mitigation methods for Rolling Noise

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