Acoustic properties of several track types

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Abstract
Railway rolling noise is strongly influenced by the characteristics of the track. The track contribution is relevant as an input to environmental calculation models such as CNOSSOS and also affects results of type tests. In this paper, results are presented of measurement campaigns on in-service trains at seven sites in the Spanish railway network managed by ADIF and ADIF Alta Velocidad to assess the track parameters for use in CNOSSOS. The measurement configuration and procedure are described including the effects of site geometry, which affects the sound power derived from pass-by sound pressure. The track types include three different track gauges, and monoblock and biblock sleepers with various railpads and fasteners. The measurements and the processing were performed according to CEN/TR 16891 and a draft CEN standard to determine source terms. Track decay rates, transfer functions and site characteristics are presented and assessed for the tracks considered, in relation to prediction models.

Keywords: Railway noise, CNOSSOS, transfer functions

1 Introduction

ADIF Alta Velocidad, Administrator of Railway Infrastructures in Spain, carried out a project to support the national implementation of the Common EU Noise Assessment Method, CNOSSOS [1], particularly to model the noise emission of ADIF and ADIF Alta Velocidad railways. Three gauges are common in Spain, namely the Iberian gauge of 1668 mm, 1000 mm in the narrow gauge network, and 1435 mm in the high speed network.

Railway rolling noise is strongly influenced by the characteristics of the track, besides wheel/rail roughness. The track contribution is relevant as an input to environmental noise calculation models such as CNOSSOS and also affects results of type tests. In this paper, some results are presented of measurement campaigns on in-service trains at seven sites in the national railway network to assess the track contribution.

These campaigns were part of a broader project with the following aims:

1. To gather measured data of CNOSSOS input parameters (roughness and transfer functions) to evaluate the suitability of the default CNOSSOS databases to ADIF tracks and the trains that run on them.
2. To assess the need to expand databases with new categories of input parameters to the method.
3. To compare resulting CNOSSOS calculations with noise levels at reception points.
4. To define the CNOSSOS input parameters to be used by ADIF, to provide instructions for the realization of Strategic Noise Maps and to facilitate the use of CNOSSOS method with common noise mapping software.

The focus here is mainly on the acoustic characterization of the track influence, although the project included the characterization both of track types and trains. Firstly, the measurement and analysis procedures are described, followed by the site and measurement configurations and the method to obtain sound power data. Finally, track characteristics, track decay rate and transfer functions are presented, followed by comparison of measured and calculated sound levels.

2 Measurement and analysis procedures

Measurement campaigns and analysis procedures were set up to gather input parameters for the CNOSSOS prediction method for railway noise emission according to the type of infrastructure and rolling stock. The noise source types and associated CNOSSOS parameters are set out in table 1.

Table 1: Main noise sources and CNOSSOS input parameters for trains and tracks

	Source type	CNOSSOS Parameter
Train characteristics	Traction Noise	Engine Type, traction noise spectrum
	Aerodynamic Noise	Aerodynamic spectrum
	Rolling Noise	Wheel Roughness
		Wheel-Rail Contact Filter
		Vehicle Transfer Function
Track characteristics		Track Transfer Function
		Rail Roughness
	Impact Noise	Additional roughness

The general principle is to use, as far as possible, the default values set by the CNOSSOS method (Tables G-1 to G-6 in 996/2015/EU). This project already considered the amended CNOSSOS default values (contact filter values) published in the Commission Delegated Directive (EU) 2021/1226 of 21 December 2020 [2] and anticipated in the RIVM Report in 2019 [3]. It was also decided only to create new categories when clearly justified by significant differences in measured noise levels. The following steps were taken.

Grouping of train and track types

The various types of trains and tracks and their physical characteristics were grouped based on information from the main railway operator in Spain (RENFE) and the infrastructure manager, as a basis to configure the measurement campaigns and to facilitate interpretation of obtained results and their extrapolation to the whole network.

Measurement campaigns

The numbers of pass-bys of all seven campaigns measured are listed in table 2, per track and train type.

Table 2: Overview of measurements performed for different train and track types.

	High Speed	Conventional	Freight	Narrow gauge	TOTAL
Track gauge	1435 mm	1667 mm	1667 mm	1000 mm	
Pass-bys	111	358	52	39	560
Train types	7	7	1	5	20
Track types	2	2		1	5

Measurement of CNOSSOS rolling noise quantities

The results of each measurement campaign were processed to obtain the rolling noise source quantities wheel/rail roughness, rolling noise transfer functions for track and vehicle and track decay rates. The CNOSSOS transfer functions were derived based on a recent draft CEN standard on railway noise source terms [4], using the procedure shown in figure 1 for rolling noise. The CEN TR 16891: 2016 technical report [5] was applied to obtain the combined roughness, the decay rates of the tracks and transfer functions with the TNO Pass-by Analysis software (PBA), using vertical rail vibrations. In addition, direct rail and wheel roughness was measured independently, as it is a specific means of noise control. Rail roughness was found to be

sufficiently low at all sites. Where not covered by the above, the EN ISO 3095: 2013 standard [6] was applicable.
The results were grouped according to the type of train and/or track, so that the values of each parameter are obtained, which according to the measurements, would best represent the acoustic emission.

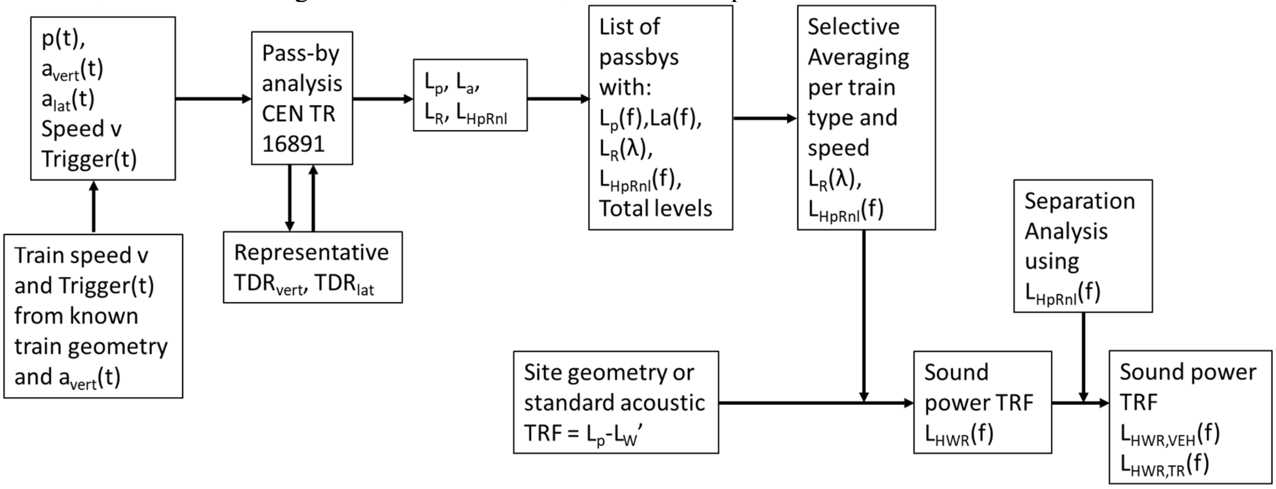

Figure 1: Analysis procedure to obtain sound power source terms for rolling noise, as given in the CEN draft standard for railway noise source terms. Pass-by sound pressure p(t) and rail vibration a(t) are used to drive track decay rates (TDR), combined effective roughness L_R and transfer functions L_{HpR}. CNOSSOS transfer functions are then obtained from the site-specific transfer functions $L_{HpW} = L_p$-$L_{W'}$. A total sound power transfer function L_{HWR} is then derived which is separated into a track and vehicle part.

Comparison and selection of CNOSSOS parameter values
The measured parameter values were compared with the default CNOSSOS transfer function and roughness spectra, selecting the most appropriate values (new or selected default ones) in each case. Also, a sensitivity analysis was performed to compare pass-by spectra applying default CNOSSOS values or measured parameter values.

Comparison of calculation and measurement
The results of CNOSSOS calculations of pass-by noise levels at 7.5 m were compared with measured levels, $L_{pAeq,tp}$ in each campaign, applying the preselected options for each parameter (Table 1). The pass-bys were chosen to correctly represent the emission covering the widest range of operational train speeds possible. In this comparison, both the infrastructure and rolling stock parameters were taken into account. Subsequently, a final decision on input parameters was made considering differences between calculated and measured overall noise levels and spectra, being as close as possible to the actual characteristics of each type of train and/or infrastructure.

Other sources
The contribution of traction noise and aerodynamic noise were also included in the analysis. The effect of impact noise was analyzed in a specific way and for this purpose, two measurement campaigns were performed. These analyses are not discussed in this paper.

3 Measurement configurations and sound power analysis

3.1 Microphone measurement configurations

The microphone measurement configurations were selected based on the site accessibility and geometry, following the preferences from the CEN draft standard for source term measurement. This recommends EN ISO 3095 positions, but also states preference for the high microphone (3.5m height) and over-ballast measurement (see fig 2a/b and 3). Most of the sites selected had two tracks with service trains in operation. Both heights of 1.2 m and 3.5 m above rail surface at 7.5m distance from the track centreline were used, to allow for potential propagation differences. Only the near track was measured at single tracks (fig 4) and at high speed lines, due to the perimeter fences, which are often at 8 m distance or more from the track.

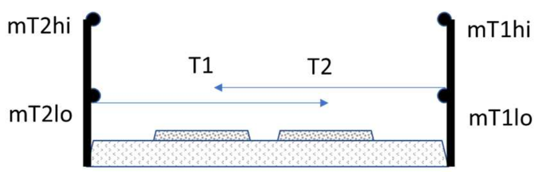

Figure 2-a. Over-ballast propagation, using standard ISO positions.

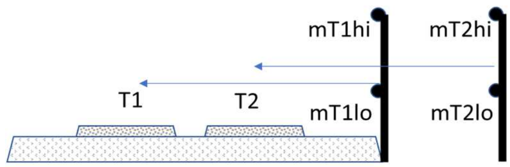

Figure 2-b. Near track and over-ballast propagation, using standard ISO positions.

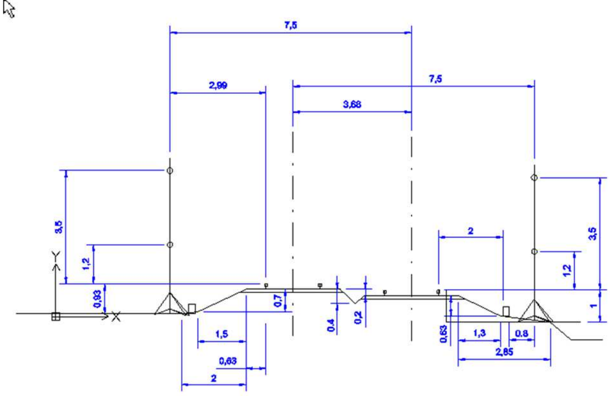

Figure 3: Measurement and site geometry for conventional line at Galapagar (as in fig 2a)

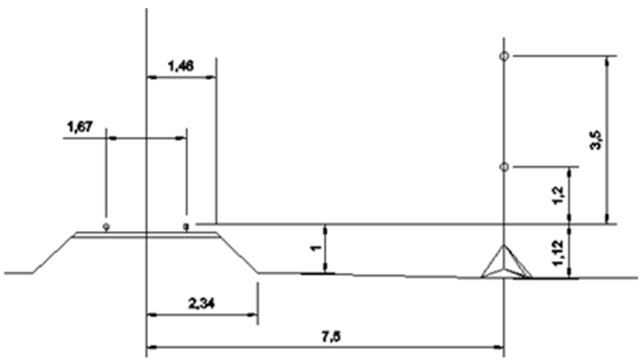

Figure 4: Measurement and site geometry for single track conventional line at El Tejar. Near Track as in fig 2b mT2lo and mT2hi.

3.2 Apparent sound power from sound pressure

Railway noise source terms are often 'apparent' sound power level per metre $L_{W'}$, i.e. the sound power derived from the specific microphone positions. The apparent sound power level is obtained from backward propagation, including the direct sound path (free field), the reflected path and diffraction over the ballast. This depends on the specific site and track geometry such as shown in figs 3 and 4. Also, the lateral and vertical source directivities are included specific to the calculation model, in this case CNOSSOS.

A site-specific transfer function for excess attenuation L_{HpW} can be calculated using a model or taken from tabulated values such as developed in the draft CEN Source terms standard. It is defined as

$$L_{HpW} = L_{peq,tp} - L_{W'}, \qquad (1)$$

where $L_{peq,tp}$ is the pass-by sound pressure level as in EN ISO 3095, and $L_{W'}$ is the apparent sound power level per metre of the source considered.

Here the transfer function L_{HpW} was calculated following the guidelines in the CEN Source terms draft standard. Some examples are shown in figures 5-a to 5-d. The general trend is a slightly rising line for the free field condition, which is due to the vertical directivity included in the CNOSSOS model. But for most situations, also reflection and diffraction effects appear, as seen in the graphs. These show a higher level at low frequencies, followed by several reflection dips. Also, the number and positioning of sources can affect the results.

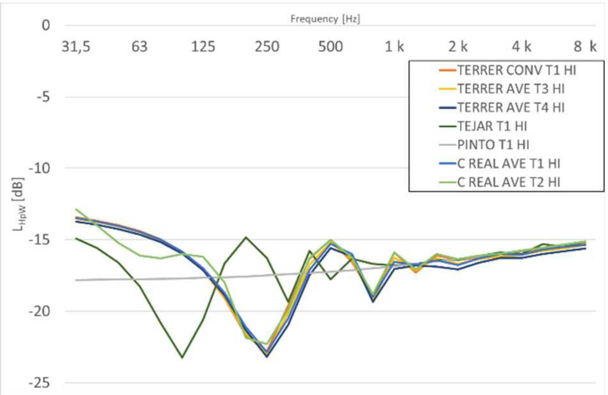

Figure 5-a: Transfer function L_{HpW} over the ground (Excess attenuation) for high microphone positions

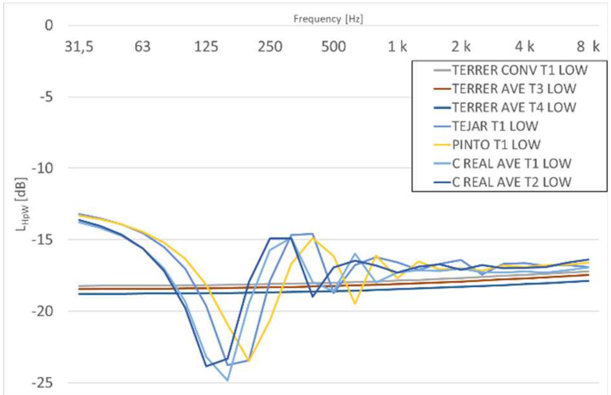

Figure 5-b: Transfer function L_{HpW} over the ground (Excess attenuation) for low microphone positions

These are 7 transfer functions of the microphone locations where sound propagates over the ground from the nearest track. (Terrer site Conventional Line T1, Terrer site High Speed Line T3 and 4, Ciudad Real site High Speed Line T1 and 2, Tejar site Conventional Line T1, Pinto site Conventional Line T1).

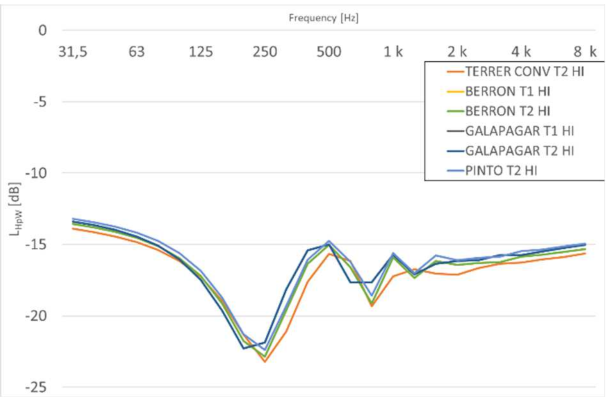

Figure 5-c: Transfer function L_{HpW} over the track (Excess attenuation) for high microphone positions

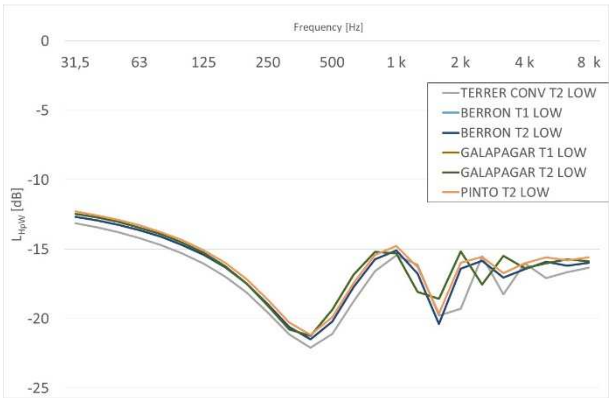

Figure 5-d: Transfer function L_{HpW} over the track (Excess attenuation) for low microphone positions

As the uncertainty in this type of function may be significant, depending on the real site geometry and modelled geometry, it is preferable to apply a moderate value if possible, by position selection or by averaging (the draft CEN Source terms standard provides an average over several site geometries).

The preference for the high position and over-ballast measurement seems to be somewhat supported by the smaller spread in transfer functions in figs 5-a and c, and fig 5-c compared with figs 5-a.

The draft CEN standard gives preference to the over-ballast measurement and to the high microphone, but at most sites the difference between the low and the high microphone was found to be relatively moderate, as shown for example in figure 6. The difference between the near (7.5 m) and far (11.2 m) microphones was also found to be relatively small as shown in the example in figure 7.

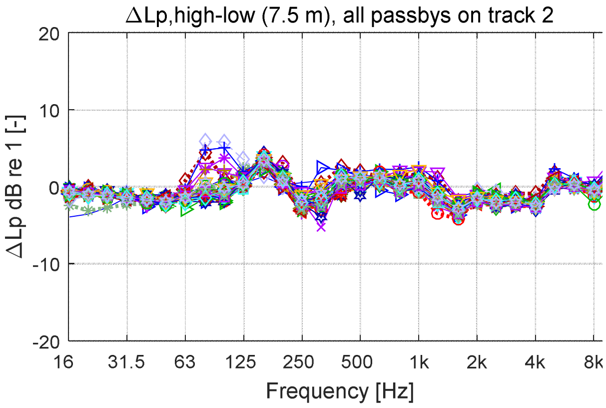

Figure 6. Difference between high and low microphone for several pass-bys on one track at Pinto site

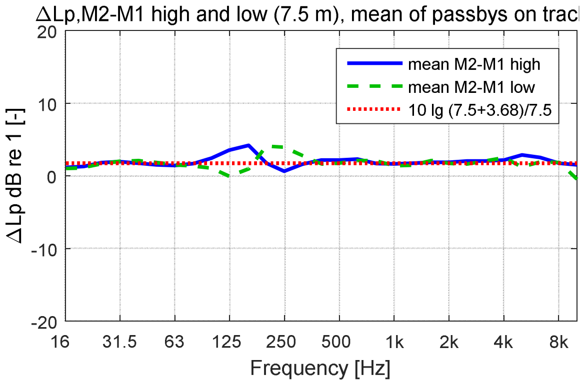

Figure 7: average difference between over track and near track microphones for high and low positions, and calculated with 10 lg d distance free field correction. Series of pass-bys on track 2 at Pinto site.

4 Track characterization

CNOSSOS calculations have five input parameters to calculate railway rolling noise, two referred to the track (roughness and transfer function) and three to the vehicle (roughness, contact filter and transfer function). Firstly, decisions on track input parameters were adopted to enable later analysis of the vehicle parameters.

Considering the information provided by the infrastructure manager on track gauge, ballast platform, sleeper type, railpad, fastener, vertical static stiffness, 8 acoustic track classes were proposed, most of which were included in the measurement campaigns: two for high speed lines, two for conventional lines with concrete mono-block sleepers, one for conventional lines with concrete biblock sleepers, one for narrow gauge network with concrete monoblock sleepers, track with wooden sleepers and lastly, slab track.

The analysis performed for one of the monoblock track classes is shown below, as an example of how the procedure presented in section 2, was applied.

4.1 Monoblock track

The description of the track provided by ADIF as infrastructure manager is the following: track gauge of 1667 mm, on mono-block sleepers, with a static stiffness declared of 100 MN/m, being higher than the other class in conventional lines with static stiffness of 85 MN/m.

Two measurement campaigns were devoted to the characterization of this track type at the site of Tejar (54 pass-bys) and Galapagar (118 pass-bys). At both sites four train types were measured (types 446, 450, 465 and freight trains) at speeds between 50 and 100 km/h. Additionally to those at Galapagar, two regional trains were measured (types 449 and 599).

4.1.1 Track decay rates

Track decay rates are not actually input data for CNOSSOS but help to characterise the track and understand the transfer functions. A low track decay rate usually points towards lower dynamic stiffness and higher track transfer function. Analysis with PBA allows to determine track decay rates following CEN TR 16891:2016 (CEN Technical Report on Measurement method for combined roughness, track decay rates and transfer functions). The vertical track decay rates derived for the Galapagar and Tejar sites are presented in figure 8. The spectrum falls below 4 dB/m at 800 Hz potentially indicating a soft support for monoblock sleepers.

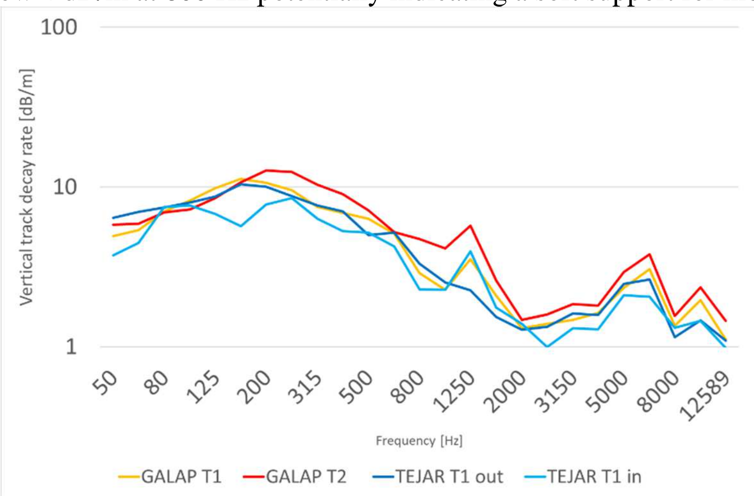

Figure 8: Spectrum of vertical track decay rates in [dB/m] in third octave bands for the Galapagar and Tejar sites, derived from pass-by rail acceleration time signals.

4.1.2 CNOSSOS track transfer function $L_{HWR,TR}$

The Pass-by Analysis (PBA) applied to the measurements produces total transfer functions $L_{HpR,nl}$ (from combined roughness to total sound pressure). A further conversion is made to obtain CNOSSOS total transfer functions $L_{HWR,n}$ in third octave bands from the PBA transfer function $L_{HpR,nl}$, and the excess attenuation function L_{HpW} (see formula (1)) following

$$L_{HWR,n} = L_{HpR,nl} - L_{HpW} \qquad (2)$$

Considering their spectrum range dominated by the track contribution (from 200 to 2KHz) the track transfer functions $L_{HWR,TR}$ were derived per train type and site (examples in fig 9-a and 9-b).

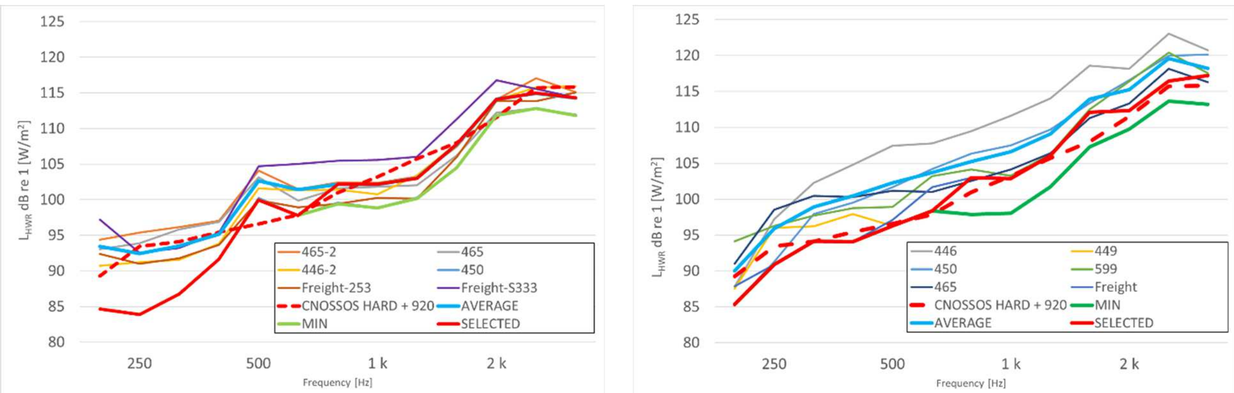

Figure 9-a. Total Transfer Function (L_{HWR}) at the Tejar site per train type, compared to CNOSSOS input data for hard monoblock track (red dashed line)

Figure 9-b. Total Transfer Function (L_{HWR}) at the Galapagar site per train type, compared to CNOSSOS input data for hard monobloc track (red dashed line)

The process to aggregate these transfer functions into one per site differs per frequency range. The transfer function must be dominated by rolling noise. However, it is known that below 500 Hz, it can be influenced by sources (traction/auxiliary), other than rolling noise. Expert criteria are needed to make this analysis and different procedures are applied per site to select the best spectrum that represent the track transfer function (red line in figures 9-a and 9-b): either to select the minimum LH per train type in the low to medium frequency range, or to select the transfer functions derived for the train types with higher roughness, being ones that create higher rolling excitation of the track.
For the **Tejar site** below 630 Hz, minimum values of the average L_{HWR} per train type were selected (green line in figures 9-a and 9-b) to represent the track part $L_{HWR,TR}$. Minimum values correspond to train types with higher roughness (type 450 and freight trains). On the other hand, the upper part of the spectrum of the selected L_{HWR} is the average (blue line in figure 9-a and 9-b). The selected L_{HWR} compares reasonably well with the CNOSSOS default input spectrum for hard monoblock track. Higher deviations are 3 dB at 500 Hz (selected L_{HWR} higher than CNOSSOS value) and the opposite at 1.25 KHz.

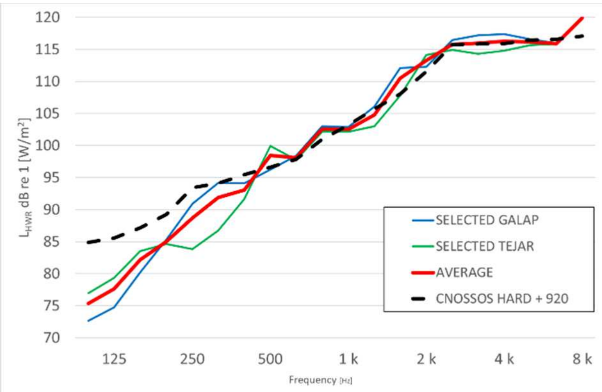

Figure 10. Average Total Transfer Function (L_{HWR}) of both sites, compared to CNOSSOS input data for Total L_{HWR} for hard monoblock track and wheel diameter 920 mm (black dashed line).

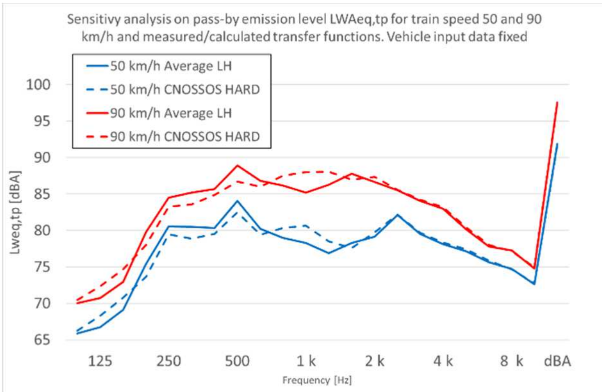

Figure 11. Comparison of calculated $L_{WAeq,tp}$ spectra based on average measured Transfer Functions L_{HWR} and on CNOSSOS default data for hard monoblock track.

For the **Galapagar site** below 630 Hz, again minimum values of the average L_{HWR} per train type were selected, which corresponds to train type 446. Above 630 Hz, L_{HWR} values for freight trains were selected. The CNOSSOS default input spectrum for hard monoblock track seems representative for the track. Deviations are seen at 800 and 1.6 KHz, with L_{HWR} higher than CNOSSOS default values.
Total Transfer Functions selected per site were averaged over available pass-bys. The result in figure 10 shows how close it is to CNOSSOS default values. The main deviation is at 500 Hz where CNOSSOS is still lower, due to the differences found at the Tejar site.

As track input data for CNOSSOS contributes to the acoustic emission of several types of trains, a sensitivity analysis was carried out to quantify the effect of this decision in the overall sound power levels. CNOSSOS algorithms were applied to calculate rolling emission with the average measured LH (solid line in figure 11) and with the spectrum based on CNOSSOS defaults for monoblock hard track (dashed line). For this analysis vehicle input data were fixed to disc wheel roughness, contact filter for wheel load of 25kN and diameter of 920 mm. The amended CNOSSOS Track-Wheel Contact Filter default value was applied [2].

The effect on global emission levels of using the CNOSSOS default input instead of the calculated LH and select data is below 0,5 dB; although spectra show differences up to 2dB at 500 Hz or -3 dB at 1KHz. It can be noted that the shape of the spectrum at 500 Hz is well predicted with CNOSSOS default values.

4.1.3 Comparison with noise level measurements

The final step to validate the proposal of the CNOSSOS input parameters was to compare pass-by noise pressure levels at 7.5 m, measured according to ISO 3095 configuration. Here, two pass-bys of a type465 train are presented as an example in table 3 and figure 12.

Table 3: Description of two pass-bys of type 465 train selected for the validation at Tejar and Galapagar sites and results of the comparison between measured and calculated values.

Running speed	75 km/h	94 km/h
Campaign	Tejar	Galapagar
Track type	Mono-bloc on hard rail pad	
Measured level (dBA)	74,0	77,5
Calculated Level CNOSSOS (dBA)	76,0	78,3
Difference	-1,9	-0,9

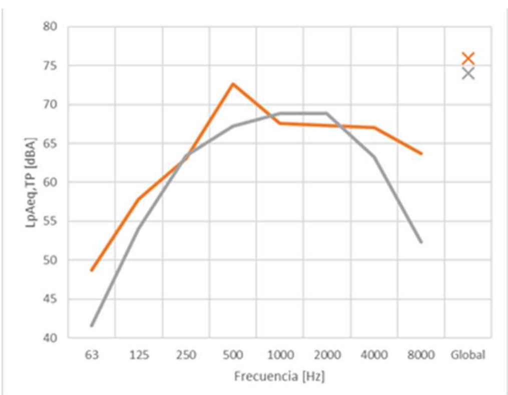

Figure 12-a. Comparison of A-weighted pass-by sound levels, measured (grey line) and calculated (orange line) at 75 km/h, Tejar site.

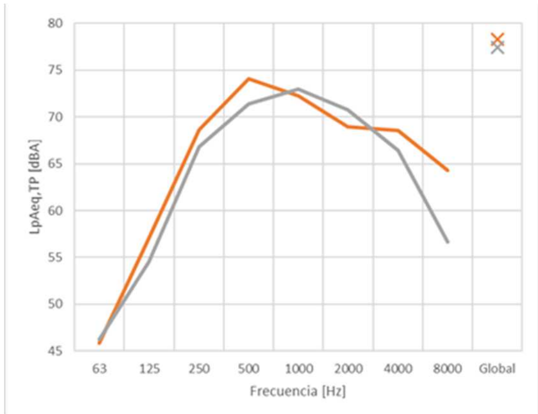

Figure 12-b. Comparison of A-weighted pass-by sound levels, measured (grey line) and calculated (orange line) at 94 km/h, Galapagar site.

Frequency	63	125	250	500	1 K	2 K	4 K	8 K
MEASURED	41,6	54,0	63,4	67,2	68,9	68,8	63,2	52,3
CNOSSOS	48,7	57,8	63,0	72,6	67,5	67,3	67,0	63,7
DIFF	-7,1	-3,8	0,4	-5,4	1,3	1,5	-3,8	-11,4

Frequency	63	125	250	500	1 K	2 K	4 K	8 K
MEASURED	46,2	54,5	66,9	71,4	73,0	70,8	66,4	56,6
CNOSSOS	45,9	57,0	68,7	74,0	72,3	68,9	68,6	64,3
DIFF	0,3	-2,5	-1,8	-2,7	0,7	1,9	-2,2	-7,7

Calculated pass-by sound levels fall within ± 2 dB of measured levels. This range was defined as acceptable in the quality criteria for CNOSSOS immission levels. In addition, calculated results generally are higher than measured, which suggests CNOSSOS does not underestimate acoustic impact. In octave bands, larger differences of 3-5 dB are seen in the 125 Hz, 500 Hz and 4 kHz for the Tejar site, but only up to 3 dB at 500 Hz for the Galapagar site.

ADIF track experts assessed the tracks at the Tejar and Galapagar sites as having hard railpads, being representative of the oldest railway network.

5 Conclusions

Railway noise source term measurements were performed at seven different sites in Spain, with different track gauges and characteristics, and a variety of train types, with the aim to evaluate whether CNOSSOS default input data could be used or other values would be required. The first analysis focused mainly on rolling noise, in particular the track contribution. In general, a good correspondence was found between measured and calculated noise levels based on CNOSSOS defaults, to within ± 2 dB.
The CNOSSOS default spectra for transfer functions were found to fit reasonably well with the average measured values.

For some train pass-bys, the influence of traction or aerodynamic sources was minimised by considering the combined wheel-rail roughness level and taking the minimum transfer function occurring for the highest wheel-rail roughness levels. This requires some expert judgment. In any case, the final selected track transfer function should be verified, comparing measured noise levels $L_{pAeq,Tp}$ and calculated values using the choices made for each CNOSSOS input parameter. In terms of track decay rates, three characteristics were found: soft pads on the high speed lines, medium and hard pads on the other lines.

The site geometry, microphone positioning, train speeds and source characteristics are key to obtain reliable data from which to derive source terms. The methodology and procedures from the draft CEN standard on source terms and CEN TR 16891 were applied to obtain the combined roughness, track decay rates and transfer functions from vertical rail vibration. At several sites the high and low microphone positions produced similar spectral results. Also, the positions measuring over ballast (far track) or by the near track tended to give similar results for the sites considered.

The project led by ADIF Alta Velocidad to study the CNOSSOS-EU implementation for modelling railway noise will allow not only a more precise calculation of its acoustic impact, but also to better understand the contributions on it of different elements of the system vehicle-track. Both the main train operating company RENFE and the infrastructure manager ADIF and ADIF Alta Velocidad have been involved in the decisions adopted in the project. Another important result of the project is data collected to study the effect of train and track maintenance strategies, that could be the base for future analysis to reduce noise emission and update calculation conditions accordingly.

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