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Improving The Source Model For Railway Bridges Of CNOSSOS

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ABSTRACT

The common European method for environmental noise computations [1], to which we refer here as CNOSSOS, incorporates a simple description of the noise emission from railway bridges. The method expresses the noise radiated by the bridge structure as a constant (flat spectrum) to be added to the rolling noise spectrum. This paper proposes two modifications that will improve the reliability of noise prediction in the vicinity of railway bridges. Firstly, the directivity of bridge noise, which is modelled in CNOSSOS as a dipole, is to be replaced by monopole characteristics. Secondly, it should become possible to use a frequency-dependent spectrum for the excess noise, instead of the flat spectrum in the CNOSSOS definition. This paper describes the issues with the current model description and it substantiates the modifications that are proposes to the method description. It also tabulates parameter values that can be used as default. In the course of 2019 it will be become clear if the proposed modifications to CNOSSOS will be accepted.

Keywords: Noise, Railway Bridges, Source Model
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1. INTRODUCTION

In the CNOSSOS source description the total sound power $L_{W,0,\text{rolling-and-bridge}}$ of the train running on the bridge is written as [1]:

$$L_{W,0,\text{rolling–and–bridge},i} = L_{W,0,\text{rolling-only},i} + C_{\text{bridge}} \quad \text{dB}, \qquad (1)$$

where C_{bridge} is a constant that depends on the bridge type, and $L_{W,0,\text{rolling-only}}$ is the rolling noise sound power that depends only on the vehicle and track properties (index i denotes frequency bands).

The necessity of changing this formulation will be treated in the next section of this paper. Before doing so, a more general treatment of bridge noise is given here, for which Equation (1) can be regarded as a special case. As the railway bridge is excited by

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the vibrating rails, the sound power of the vibrating bridge can be expressed in term of roughness and a transfer function. Similar to the CNOSSOS formulations for rolling noise, the sound power caused by a vehicle on a bridge can be written as

$$L_{W,0,\mathrm{bridge},i} = L_{R,\mathrm{TOT,i}} + L_{H,\mathrm{bridge},i} + 10 \times \lg (N_a) \quad \mathrm{dB}, \qquad (2)$$

where $L_{H,\mathrm{bridge}}$ is the transfer function from the total effective roughness to the sound power per vehicle. The other quantities are exactly as defined in the CNOSSOS document [1]. Using this formulation for the bridge noise, Equation (1) can be written as

$$L_{W,0,\mathrm{rolling–and–bridge},i} = 10 \times \lg (10\ L_{W,0,\mathrm{rolling\text{-}only},i} /10 + 10\ L_{W,\mathrm{bridge},i}/10) \ \ \mathrm{dB}. \quad (3)$$

So far, we have not necessarily changed the output of the CNOSSOS source model, we have only rewritten the original equations. By choosing appropriate values for $L_{H,\mathrm{bridge}}$, the output of Equation (3) will match that of Equation (1).

The modifications that are proposed are as follows:

- A new text version of the section Correction for structural radiation (bridges and viaducts) is required, introducing the bridge noise sound power $L_{W,0,\mathrm{bridge}}$ and the bridge transfer function $L_{H,\mathrm{bridge}}$. CNOSSOS equation (2.3.18) is replaced by equation (2) above.
- In the CNOSSOS section on Source directivity it should be added that omni-directionality is assumed for bridge noise in the horizontal plane, while the rolling noise keeps its dipole directivity. (Note that because of this, the quantity $L_{W,0,\mathrm{rolling–and–bridge}}$ has lost its functionality and can be omitted.)
- Table G-7 is replaced by a table with default values for the bridge transfer function $L_{H,\mathrm{bridge}}$. Table G-3 is extended with an example track transfer function for direct fastening systems that are found on steel and concrete bridges.

These modifications for bridge noise are part of larger set of corrections and improvements proposed for other parts of CNOSSOS, about which the European Commission will most likely decide in the course of 2019 [2].

2. WHY ARE THESE MODIFICATIONS NEEDED?

The following two issues have been identified after comparing the present model's output with the CNOSSOS quality framework that aims at an uncertainty of less than ±2 dB(A). It will be shown that only adjusting the input values will not be sufficient to reach the quality goal. This is particularly relevant because the uncertainty is exceeded at obvious hot spots of the railway system: steel bridges.

2.1 Flat spectrum

The excess noise radiated by steel and concrete bridges may take many spectral shapes, but a flat spectrum is very unlikely. Of course, this was known during the development process of CNOSSOS. Considering a whole railway network, bridges make up less than 1 percent of the track length in most countries and because of that, it may have seemed fair to regard bridges as a particularly noisy stretch of track, as it is now in CNOSSOS. Unfortunately, declaring that C_{bridge} is a constant deprives EU Member States of taking advantage of their potentially available spectral measurement data or noise classification systems for bridges. It will not be a large step to replace this constant by a frequency dependent term $C_{\text{bridge},i}$ which, of course, can still be set to a constant if no spectral information is considered necessary. Besides this, the maximum value of 9 dB listed in table G-7 of CNOSSOS will unfortunately not be sufficient for some noisy bridges. Excess noise up to 20 dB would be no exaggeration.

2.2 Directivity

The main issue with the CNOSSOS method, however, is that the source directivity of bridge noise in the horizontal plane cannot be approximated by a dipole line source. This is due to the fact that most bridges are made of main girders and cross girders, deck plates, web stiffeners with different directivity characteristics. Because of this mix of directivity patterns and source strengths, and also because of shielding effects and reflections between bridge components, monopole characteristics may be considered more appropriate for bridge noise, see for example the book by Thompson [3].

The measurements described hereafter demonstrate that a model that assumes dipole characteristics tends to underestimate the noise radiation in directions that are almost parallel to the track [4]. For small angles φ, where φ is defined in the horizontal plane (see Figure 1), high levels with a considerable amount of low frequency energy are measured near railway bridges. Most often, in these directions residential areas can be found. This stresses the importance to model the directivity of the bridge properly.

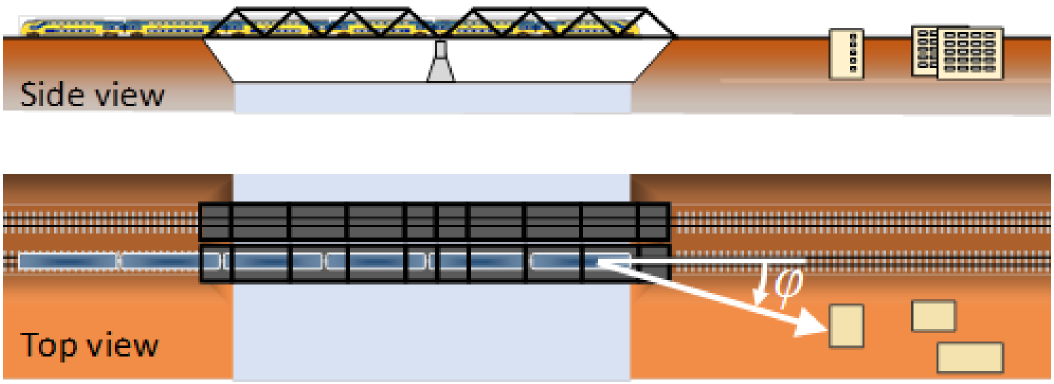

Figure 1 Residential areas near railway bridges.

On two steel bridges in the Netherlands, the Vink bridges near Leiden and the Baanhoek bridge near Sliedrecht, noise measurements were performed in 2015. Measurement site A was near the centre of each bridge, a reference site B was at the embankment along the track adjacent to each bridge (same distance). The noise from train pass-bys is measured at the two microphone positions simultaneously. This way, the angle φ for position B equals only 2-3° for one bridge and 12° for the other bridge. Further details can be found in Table 1.

The level difference in the 63 Hz octave band between both positions has been determined for the short period of time that the train is on the bridge (at that time the train has already completely passed position B). This level difference is refered to hereafter as 'attenuation'. Furthermore, the attenuation in the 1 kHz octave band is determined. The results of the measurement are given in Table 1.

The table also shows calculation results for two versions of the Dutch calculation model RMR for noise mapping. The 1996 version is known with respect to noise mapping in the European Union as the former "interim method for railway noise RMR". This method featured dipole characteristics for both rolling noise and bridge noise. In this respect, the 1996 has the same approach as the CNOSSOS method. From 2006 onwards, the RMR method assumes monopole characteristics for the bridge noise and still dipole characteristics for the rolling noise.

Table 1 Noise attenuation at 63 Hz and 1 kHz.

	Vink bridges (Leiden)	Baanhoek bridge (Sliedrecht)
Measurement date	7-12-2015	9-10-2015
Bridge type	Drawbridge with pi-girders	Bowstring bridge with pi-girders
Length of bridge	14 m	223 m
Distance point B to track	16 m	11 m
Distance point B to centre of bridge	132 m	250 m
Angle φ	12 degrees	2-3 degrees
Attenuation at 63 Hz (level difference between B and A)	**-15 dB** measured **-18 dB** RMR 2006 mono+dipole* **-22 dB** RMR 1996 dipole	**-20 dB** measured **-17 dB** RMR 2006 mono+dipole* **-35 dB** RMR 1996 dipole
Attenuation at 1 kHz (level difference between B and A)	**-31 dB** measured **-27 dB** RMR 2006 mono+dipole* **-28 dB** RMR 1996 dipole	**-28 dB** measured **-31 dB** RMR 2006 mono+dipole* **-37 dB** RMR 1996 dipole

* monopole for bridge noise, dipole for rolling noise.

The analysis shows that the attenuation in the 63 Hz band is described reasonably well by the RMR 2006 method. The difference between the calculated and measured value in this octave band is only -3 dB for one bridge and +3 dB for the other. The attenuation of the dipole model (RMR 1996) is exaggerated by -7 and -15 dB for these bridges, respectively. In the 1 kHz octave band both models predict the attenuation equally well for the first bridge (14 m length). For the second bridge (223 m) the RMR 2006 model is much closer to the measurement results.

It should be noted that the contribution from the bridge in the 63 Hz band under these angles and at these distances to L_{den} is still relevant, because of the strength of the low frequency source power of the railway bridge. Ignoring the monopole characteristics of the bridge in the model, would lead to an underestimation of L_{den} and certainly it would temper the need to mitigate the bridge noise when it comes to action plans for ‘hot spots’.

3. PROPOSAL FOR IMPROVED BRIDGE SOURCE MODEL IN CNOSSOS

3.1 Measured noise spectra and attempts for classification

There are many types of steel and concrete bridges, ranging from special designs (designed to be silent) to extremely noisy bridges.

During a noise measurement programme from 2015 to 2017, over 25 bridges near residential areas in the Netherlands have been measured. For each train pass-by on a bridge, the difference spectrum has been determined, defined as the total noise measured on the bridge minus the rolling noise on standard ballasted track. The resulting ‘bridge gain’ is the average of the difference spectra of at least 5 train pass-bys on that bridge.

Figure 2 shows the bridge gain of the 21 steel bridges in this campaign (thin lines). These have been divided in three groups: eight bridges with +5 ± 2.5 dB(A), ten bridges with +10 ± 2.5 dB(A), three bridges with +15 ± 2.5 dB(A). The group averages are displayed as dotted lines.

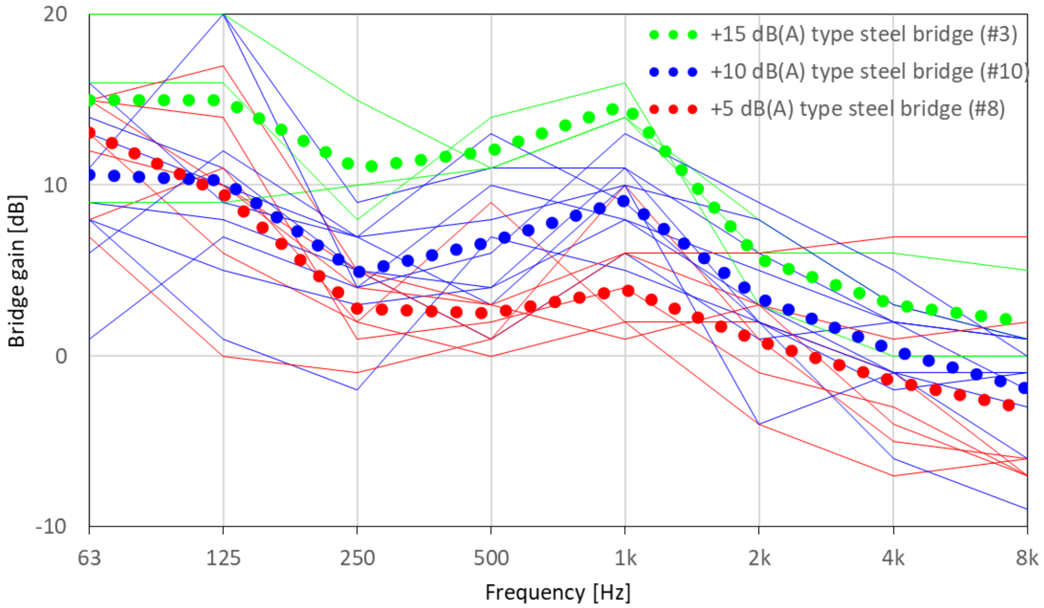

Figure 2 Bridge gain spectra of 21 steel bridges and three averages [4].

An attempt has been made to find a relationship between the bridge gain and design properties of the bridges, based on construction drawings. This exercise showed no clear correlation between bridge design and bridge gain, apart from cases with extremely low and extremely high bridge gain. Composite steel/concrete designs with a concrete deck plate (over 30 cm thick) underneath a ballasted track had a gain close to 0 dB(A). And among the noisiest types were steel bridges with wooden sleepers directly on top of the girders (no ballast layer). Construction engineers suggested that these may be particularly noisy because the shape of the sleepers will deform over time, resulting in clearance between sleepers and deck or girders, causing stamping of sleepers during wheel pass-bys. But for most other types, no practical classification based on design features could be developed.

3.2 Bridge and track transfer functions

It is important to realise that along with the bridge transfer functions also the track transfer function needs carefull consideration. The track system of the "+10 dB(A)" and "+15 dB(A)" bridges of the previous section, for example, deviates from ballasted track. A direct fastening system is applied on these bridges, see Figure 3. Direct fastening is applied on steel as well as concrete bridges. Among the "+5 dB(A)" group were some steel bridges with embedded rails, see Figure 4.

A change in stiffness of the track system on the bridge will affect the bridge vibration as well as the track vibration. This property is sometimes exploited as a noise measure. By applying a softer baseplate, the rail is decoupled and this will reduce the vibration energy transfered into the bridge. If the resulting decrease of bridge noise is greater than the increase of rolling noise, the overall noise is reduced.

From the above it follows that, apart from bridge transfer functions, there is a need for dedicated track transfer functions such as direct fastening and embedded rail, and other frequently applied systems on bridges. Note that this is not a consequence of the modifications proposed in this paper. Even without these modifications, EU Member States will need to extend the CNOSSOS library (table G-3) with track systems that have significantly different acoustical behaviour than ballasted track.

Figure 3 Direct fastening on concrete (left) and steel parts (right) of the large bridge across the river IJssel in Deventer. Photo by Movares.

Figure 4 Transition from embedded rail (left) to ballasted track (right) on a steel bridge across the river Roer in Roermond. Photo by Movares.

It is possible to determine track and bridge transfer functions for each individual railway bridge, after measuring noise and/or vibration of that bridge. Various methods can be developed for this. By measuring rail vibration along with noise, it is possible to characterise a bridge in more detail [5, 6]. A different approach is given in the next section. Is is shown how this approach is used to obtain average bridge transfer functions that are proposed as defaults for CNOSSOS.

3.3 Deriving transfer functions for use in CNOSSOS

In order to derive the bridge transfer function $L_{H,\mathrm{bridge}}$ using the measured bridge gain $C_{\mathrm{bridge,i}}$, the rolling noise must be subtracted from the total noise in the following way:

$$L_{H,\mathrm{bridge},i} = 10 \times \lg \left(10\ L_{H,\mathrm{rolling\text{-}and\text{-}bridge},i}/10 - 10\ L_{\mathrm{H,rolling},i}/10\right) \qquad \mathrm{dB}, \qquad (4)$$

where $L_{H,0,\text{rolling–and–bridge},i} = L_{H,0,\text{rolling-only},i} + C_{\text{bridge},i}$. This equation will be evaluated in this section for steel bridges with direct rail fastening. Concrete bridges and steel bridges with embedded rails are discussed in the next section.

The rolling noise for the "+10 dB(A)" and "+15 dB(A)" bridges from the previous section cannot easily be determined from noise measurements, as the bridge noise is dominating the total noise. However, in the case of direct fastening, a solution is offered by using noise spectra measured on concrete bridges with the same type of direct fastening. It is safe to assume that the noise radiated by the concrete deck itself does not contribute significantly, except for very low frequencies, see section 3.4. Neglecting this low-frequency effect, it can be stated that the rolling noise on steel bridges is approximately equal to the total noise measured on concrete bridges with the same track system. The characteristics of the Dutch direct fastenings system are given in reference [7]: baseplate 'FC6', 10 mm thick, 85 MN/m vertical stiffness. Though this reference is over twenty years old, this is still the standard type for direct fastening on both concrete and steel bridges in the Netherlands.

By applying Equation (4) to the data of Figure 2, using a so-called crossover function of Figure 6, the spectra given in Figure 7 are found. The spectra in Figure 7 are described here:

- "LH,rolling, ballasted track" is the energy sum of the default CNOSSOS ballasted track transfer function "Monoblok sleeper on medium stiffness rail pad" and vehicle transfer function "Wheel with diameter 920 mm, no measure" (both are taken from CNOSSOS table G-3).
- "LH,rolling, concrete track" is the energy sum of the track transfer function for direct fastening, derived in [4], and the vehicle transfer function "Wheel with diameter 920 mm, no measure" of CNOSSOS. Around 250 Hz the absent sleepers cause the blue curve to be below the black curve, while around 1 kHz it is the other way round: rail vibration is higher because of the low pad stiffness. It is important to mention that the track transfer function for direct fastening has been corrected for reflections from the deck.
- The dashed lines are the steel bridge transfer functions resulting from Equation (4). For frequencies above 2 kHz, Equation (4) could not be evaluated and in that range a crossover filter was used instead. More specifically, the crossover filter named "c. bow-string girder bridge 250 m long" given in Figure 6 is taken. These filters are defined as the relative contribution of the bridge noise to the total noise.

The bridge transfer functions of Figure 7 are to be used in combination with the track transfer function for direct fasteners (baseplate 'FC6', 10 mm thick, 85 MN/m vertical stiffness). Only in that case will they yield a bridge gain of +10 dB(A) or +15 dB(A), respectively. All transfer functions are given in Table 1. Bridges and tracks with other types of rail fastening systems may have different characteristics.

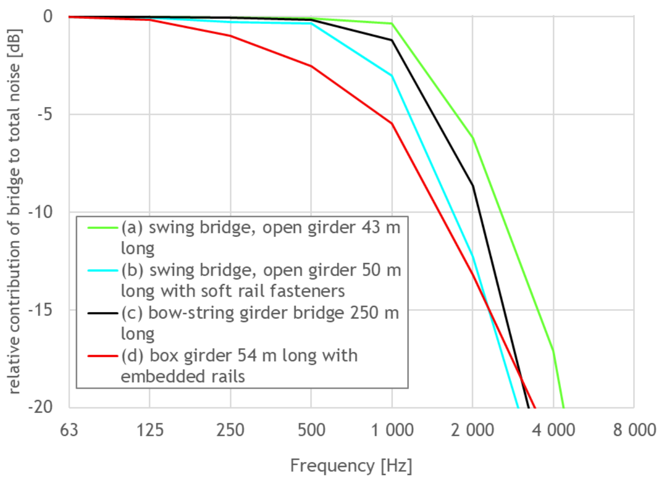

Figure 6 Crossover filters determined using results from Janssens and Thompson, published as figure 11-20 in [3].

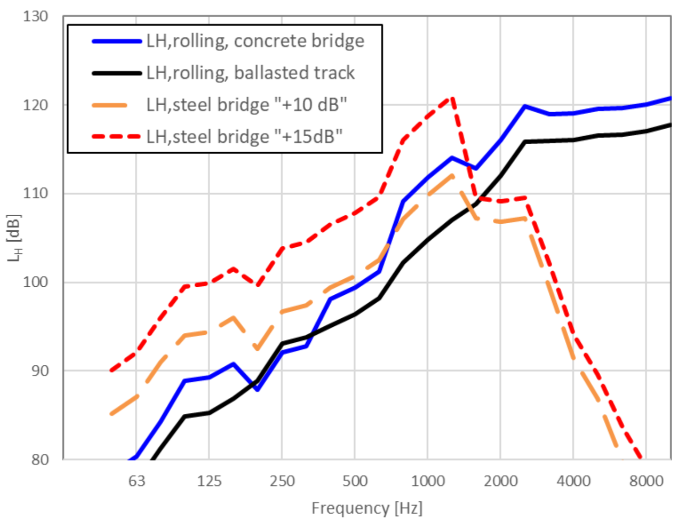

Figure 7 Rolling noise and bridge noise transfer functions.

Table 1 Transfer functions for steel bridges and for a track with direct fastening.

Freq [Hz]	$L_{H,\mathrm{bridge},i}$		$L_{H,\mathrm{track},i}$
	+10 dB(A)	+15 dB(A)	direct fastening
50	85,2	90,1	75,4
63	87,1	92,1	77,4
80	91,0	96,0	81,4
100	94,0	99,5	87,1
125	94,4	99,9	88,0
160	96,0	101,5	89,7
200	92,5	99,6	83,4
250	96,7	103,8	87,7
316	97,4	104,5	89,8
400	99,4	106,5	97,5
500	100,7	107,8	99,0
630	102,5	109,6	100,8
800	107,1	116,1	104,9
1000	109,8	118,8	111,8
1250	112,0	120,9	113,9
1600	107,2	109,5	115,5
2000	106,8	109,1	114,9

Freq [Hz]	$L_{H,\text{bridge},i}$		$L_{H,\text{track},i}$
	+10 dB(A)	+15 dB(A)	direct fastening
2500	107,3	109,6	118,2
3160	99,3	102,0	118,3
4000	91,4	94,1	118,4
5000	86,9	89,6	118,9
6350	79,7	83,6	117,5
8000	75,1	79,0	117,9
10000	70,8	74,7	118,6

3.4 Other systems

The “+5 dB(A)” group of bridges of Section 3.1 is not homogeneous with respect to the track system. Some of these bridges have embedded rails and others are equipped with direct fastening. After splitting this group into two sub-groups, “+5 dB(A) embedded rail” and “+5 dB(A) direct fastening”, it was found that the variance in bridge gain is large, making this limited data set unsuitable to derive bridge and track functions for these groups. Of course, it is always possible to estimate transfer functions for individual bridges based on measurement data [5].

Concrete bridges generally receive much less vibration energy from the rails, compared to steel bridges. Figure 8 shows that the energy transfer is about 20 dB less in all frequency bands than for steel bridges, when comparing bridges with the same rail support system. The noise radiated by concrete bridges is generally negligible unless the edge of the bridge is shielding the rolling noise radiation (acting as a barrier). If considered necessary, for example to express the low frequency radiation properly, a transfer function for a concrete bridge may be determined by measurement. Alternatively, it might be possible to estimate a concrete bridge transfer function by using the energy differences of Figure 8 in combination with Table 1. It is beyond the scope of this paper to demonstrate this.

If direct fastening is applied on the concrete deck, the rolling noise can easily be calculated using the track transfer function given in Table 1. If the direct fastening system differs from the one specified in this paper, it should be considered to derive one from measurements.

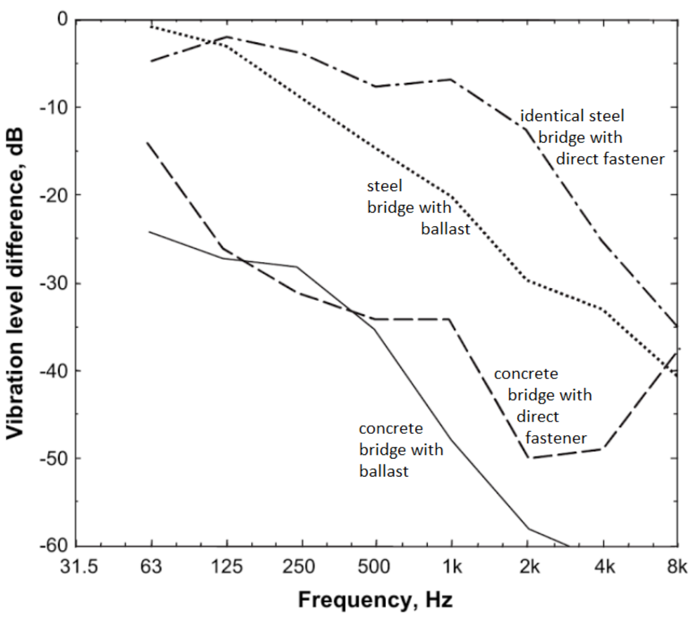

Figure 8 Measured vibration level difference between rail and bridge. Figure copied from [2], used by kind permission of David Thompson.

3.5 Barriers on the bridge

Special attention is needed for bridges that contain noise barriers. Assuming that the barriers are not acting as noise sources themselves, only the rolling noise will be shielded by them. The bridge noise will generally be radiated without much interference, for example from the sides and bottom of the bridge. Note however that barriers that are not connected to the bridge, such as barriers on the embankment or barriers close to the dwellings, will certainly shield the bridge noise. As this distinction between barriers would require a specific modelling prescription and would increase the complexity and controllability of the software, this is not proposed here as part of the modifications. A worst-case rule may avoid this issue: barriers on the edges of the bridge are generally not taken into account.

4. ACKNOWLEDGEMENTS

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