An approach to improve railway rolling noise calculations in CNOSSOS-EU: Refinement and validation using TWINS calculations

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Abstract

The reliability of CNOSSOS-EU methodology for evaluation of railway noise is dependent on the quality of input values that define the system's excitation and transfer functions. Currently available input values are limited and of insufficient quality, resulting in large errors in noise level calculations. A case study wherein railway rolling noise mitigation measures are evaluated with both CNOSSOS-EU and TWINS show deviations in resulting sound power levels of up to 8 dB(A) and 4 dB(A) for absolute and relative measures respectively. An approach to process TWINS output to extract transfer functions as input values for CNOSSOS-EU is described in this paper. The updated CNOSSOS-EU calculations correspond well with those of TWINS, with the maximum deviation limited to 1.5 dB(A) and 1 dB(A), respectively, for the same absolute and relative measures.

Keywords: railway rolling noise, freight wagon, noise source strength CNOSSOS-EU, TWINS.

1 Introduction

To address the growing problem of noise pollution in Europe, the Environmental Noise Directive (END) [1] was established and an update to Annex II of this END in 2015 [2] requires all European Union Member States to use Common Noise Assessment Methods for Europe (CNOSSOS-EU) [3] - a harmonized European calculation method - for calculating these strategic noise maps. This intention to create a common platform for all Member States to quantify their noise issues posed a challenge as the transition from the existing country-specific noise calculation techniques to CNOSSOS-EU presented obstacles especially in the context of railway noise [4].

To aid the transition, CNOSSOS-EU repository includes a database of default values for the parameters necessary to perform a source strength calculation. An interim solution was also suggested by representing the country-specific vehicle and track systems with their closest relevant default values [5]. This solution is not meant to be permanent nor accurate, with differences reported in source strength calculations of up to 10 dB(A) between old methods and CNOSSOS-EU [6], and is expected to decline in usage as countries develop their own repository of parameter values.

With the next round of strategic noise mapping approaching in 2022, there is still a lack of reliable values for the critical parameters which are the track and wheel's roughness and its acoustic behavior represented using Transfer functions (TFs). In this paper, an approach to supplement the repository of wheel and track TFs with reliable and specific values is presented. In line with suggestions by developers of CNOSSOS-EU [5], this approach processes calculations made by TWINS (Track-Wheel Interaction Noise Software) [7, 8] which is a widely accepted standard for rolling noise evaluation, to extract TFs that are suitable as input for CNOSSOS-EU.

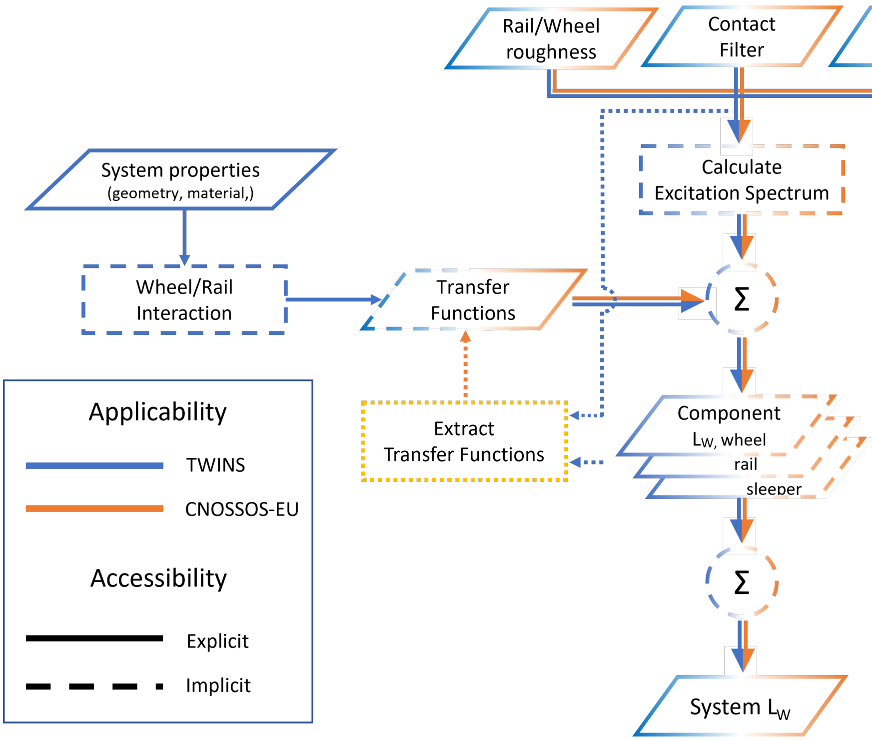

Figure 1: Flowchart visualizing common methodology shared by CNOSSOS-EU and TWINS. The steps in the flowchart representing the functions and parameters of a particular calculation method's framework are classified as follows: solid-lines imply they are explicitly defined and hence accessible; dashed-lines imply they are implicitly defined and hence inaccessible. Dotted lines denote extraction procedure described in this paper

2 Methodology

CNOSSOS-EU and TWINS calculations of railway rolling noise strength are based on a theoretical approach wherein excitation from surface roughness is amplified by the dynamic response of vibrating surfaces, hereby referred to as transfer functions (TFs). The primary difference between TWINS and CNOSSOS-EU is that the former estimates the TFs using numerical methods whereas the latter uses empirical values to simulate these interactions. Despite this difference, the principle of amplifying the input excitation with the system's TFs is similar for both methodologies and this allows for using the TFs extracted from TWINS in CNOSSOS-EU. The illustration in Fig. 1 uses a process flowchart to compare the methodologies as well as the proposed approach for extracting TFs. The CNOSSOS-EU calculations which make use of these extracted TFs while all other common inputs are identical are expected to provide results close to those obtained with the calculations entirely performed in TWINS, which is verified in Section 3.2.

The two methodologies also differ in their purpose: TWINS is primarily used for design and validation purposes at the industry and research level while CNOSSOS-EU is intended for administration-level strategic noise mapping. The difference in purpose influences the input/output specifications, and these are detailed below:

1. In TWINS, the rail and sleeper components are treated as separate components, whereas these are integrated in CNOSSOS-EU and denoted as the *track* component.

2. TWINS uses either measured or modelled decay rates. In CNOSSOS-EU, decay rates are not explicitly provided as input but are implicit in the track transfer function.

3. The frequency range considered by TWINS is 100 Hz - 5 kHz. In comparison, CNOSSOS-EU has a

larger frequency range of 63 Hz - 10 kHz.

4. L_W calculations are in $1/3^{rd}$ octave bands for TWINS, while they are made in $1/1$ octave bands for CNOSSOS-EU. Nonetheless, the input spectra for both methodologies are required in $1/3^{rd}$ octave bands.

5. The calculated rolling noise SWL is defined in TWINS as a point source with the unit *dB(A) per wheel and associated rail vibration* [7]. In CNOSSOS-EU, it is defined as a line source with the unit *dB(A) per meter* for a steady flow of vehicles.

2.1 Extraction of the transfer functions

In the calculation methodologies employed by TWINS and CNOSSOS-EU for railway rolling noise evaluation, the transfer function of a component quantifies the propagation of the system input excitation to the component SWL, as illustrated in Fig. 1. The TF of a given component is defined in $1/3^{rd}$ octave bands and is invariant with respect to the vehicle speed.

2.1.1 Total roughness calculation

The total roughness for wave number band $i - L_{R,Total,i}$ is calculated by the energetic addition of the rail and wheel roughness spectra along with a logarithmic penalty on shorter wavelengths defined by the Contact Filter. The conversion of the spatial roughness variations to the temporal excitation at the rail-wheel interface is based on the constitutive relation $f = v/\lambda$ where v is the vehicle speed, λ is the roughness wavelength and f is the frequency, all in SI units.

An excitation spectrum that follows the standard limits for $1/3^{rd}$ octave bands - $L_{R,Total,f_i}$, is obtained by energetically and proportionally adding the frequency bands of $L_{R,Total,f_i'}$ that overlap with the standard $1/3^{rd}$ octave bands [3].

2.1.2 Processing TWINS calculations

The transfer functions of the different components: wheel, rail and sleeper may be readily extracted from TWINS rolling noise SWL calculations as shown in Equation 1. Here subscript *comp* refers to the component – wheel, rail or sleeper, and $L_{R,Total,f_i}$ is the input excitation spectrum using values of the roughness spectra and contact filter that were used as input to TWINS.

$$TF_{comp,i} = L_{W,comp,i} - L_{R,Total,f_i} \tag{1}$$

The post processing of a single TWINS calculation yields three TFs, respectively associated with the wheel, rail and sleeper component, and specific to the choice of component properties.

2.2 Validation of the extracted transfer functions

The validity of the extracted transfer functions may be checked by being introduced into the CNOSSOS-EU calculations and comparing the results with those of TWINS, provided other common input parameters are identical. To allow this, a simple conversion of the default CNOSSOS-EU output to a unit that is comparable to the TWINS output is described below.

The SWL calculation framework in CNOSSOS-EU implicitly includes a conversion of the SWL from *per axle* – L_W to *per meter* – $L_{W'}$, where the latter metric accounts for the effects associated with a steady vehicle flow. The intermediate *SWL per axle* is equivalent to the *SWL per wheel and associated rail vibration* calculated by TWINS [7]. Equation 2 is used to revert the CNOSSOS-EU output back to L_W, consisting in a simple rearrangement of the implicit conversion found in Eq.(IV-2) in [3]. The conversion between the metrics is thus given by

$$L_W = L_{W'} - 10\, log(Q/1000\, v), \tag{2}$$

where Q is the vehicle volume flow in railway wagons per hour and v is the vehicle speed in km per hour given as input to CNOSSOS-EU.

3 Case Study: Comparison of rolling noise mitigation measures

Realistic train-track configurations are defined as a case study to test the presented methodology through a comparative evaluation using both TWINS and CNOSSOS-EU calculations. The motivation for the defined configuration is to quantitatively assess the effectiveness of selected rolling noise mitigation measures applied to the case of freight wagons running on a typical railway network in Sweden.

Reference calculation performed with TWINS [9] are used for comparison with CNOSSOS-EU as well as for extracting the transfer functions to refine the CNOSSOS-EU calculations. These extracted TFs are then used as input to CNOSSOS-EU calculations to validate the accuracy of the suggested approach.

Two sets of CNOSSOS-EU calculations are performed with different wheel and track TFs:

– *Default*: Uses existing TFs from the CNOSSOS-EU database

– *Updated*: Uses TFs extracted from TWINS calculations

3.1 Definition of the test cases

The rolling noise source strength and radiation may be mitigated through changes to the train-track component geometry, roughness or material properties. A noise mitigation measure may consist of one or more of these modifications implemented on a baseline train-track configuration.

In the case study considered here, the so called primary mitigation measure is a change in brake technology from freight wagons equipped with Cast-Iron brakes to Disc brakes. Secondary measures consist in possibly adding rail-grinding or rail-pad stiffening as supplementary measures. The cases are defined to evaluate the effectiveness of the primary measure and one of the secondary measures when applied either independently or in combination.

3.1.1 Baseline/Reference scenario

The baseline train-track configuration is considered to be representative of a typical freight wagon running on a railway network in Sweden. Table 1 lists the specifications of the baseline configuration. References to figures represent the input values used for the empirically-based parameters.

3.1.2 Change in brake technology

The primary mitigation measure in this case study is a change in the brake technology of the freight wagon from Cast-iron block brakes to Disc brakes. This change in technology affects two features of the wheel that contribute to rolling noise:

– Change in wheel roughness: Using Cast-Iron brakes compared to Disc brakes imply a greater wheel roughness due to the direct contact of the brake blocks with the wheel tread. Fig. 2 shows a comparison of the roughness spectra obtained from [10], with an extrapolation of the measurements in order to fit the CNOSSOS-EU wavelength range.

– Change in wheel geometry: Cast-Iron brakes have a curved web to allow for better thermal expansion of the wheel for withstanding heat generation during braking whereas Disc braking enables the use of a straight web. The strength of the wheel as a rolling noise source is controlled by its geometry and this may be seen by comparing the wheel TFs in Fig. 8.

The current database of limited default wheel TFs associated with CNOSSOS-EU makes it incapable of considering a change in wheel geometry. Therefore the CNOSSOS-EU *default* calculation will only evaluate

Component	Feature	Parameter Value	
		TWINS	CNOSSOS-EU
Wheel	Geometry†	BA308 Curved Web, 920 mm wheel diameter	920 mm wheel diameter, no measure (Fig. 8) *
	Roughness	Cast Iron brake wheel roughness (Fig. 2)	Cast Iron brake wheel roughness (Fig. 2)
	Contact Filter	Axle load 100 kN, 920 mm wheel diameter	Axle load 100 kN, 920 mm wheel diameter
Track	Rail type†	UIC-60	Mono-block sleeper on soft rail pad (Fig. 9) *
	Sleeper†	concrete mono-block	
	Rail pad†	Pandol soft studded 10mm rail pads	
	Ballast	Granite	-
	Rail roughness	Medium rail (Fig. 3)	Medium rail (Fig. 3)
	Damper	Absent	Absent

Table 1: Specifications of the baseline configuration representing a typical freight wagon on Swedish rail network. † denote features that are typically geometrically modelled in TWINS. * denote TFs to CNOSSOS-EU that are modified for the calculations *updated* to match the corresponding TWINS feature description

the impact of changing the wheel roughness, keeping the wheel TF a constant. In comparison, the updated calculations with CNOSSOS-EU will rely on wheel TFs extracted from TWINS, thereby enabling evaluating the impact of changing both the wheel roughness and geometry.

3.1.3 Rail grinding

Rail grinding is introduced as a secondary measure to better capture the reduction in wheel roughness levels obtained from a change in brake technology. The *medium* rail and *smooth* rail in Fig. 3 correspond to the roughness spectra before and after grinding, respectively, based on measurements taken on Swedish tracks. These are retrieved from roughness measurements at Järna2 and Gårdsjö respectively, reported in [13]. An extrapolation of the spectra is assumed to fit the measured data with the CNOSSOS-EU wavelength range. Fig. 4 shows the resulting total roughness in the wavenumber domain – $L_{R,Total,\lambda}$ for combinations of the two sets of rail and two sets of wheel roughness spectra. Note that the spectra in Fig. 4 include the Contact Filter.

3.1.4 Rail-pad stiffening

The stiffening of rail-pads as a secondary measure decreases the effective radiating surface of the rail thereby reducing the rail-component contribution to rolling noise. In TWINS, this change is implemented by modifying the stiffness of the rail-pad in the numerical model. This change affects the wheel-rail contact receptances and the modelled decay rate. In CNOSSOS-EU, rail-pad stiffness is implicit in the choice of Track TF. The values of rail-pad vertical stiffness chosen for this measure are based on track TFs available in the default CNOSSOS-EU database: soft (150 MN/m), medium (500 MN/m) and hard (1000 MN/m). This measure is thus implemented

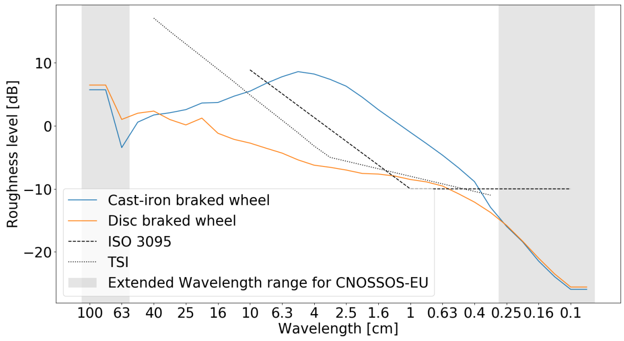

Figure 2: Typical wheel roughness spectra for Cast-Iron and Disc braked technologies obtained from [10] and plotted in comparison with ISO 3095 [11] and TSI limits [12]

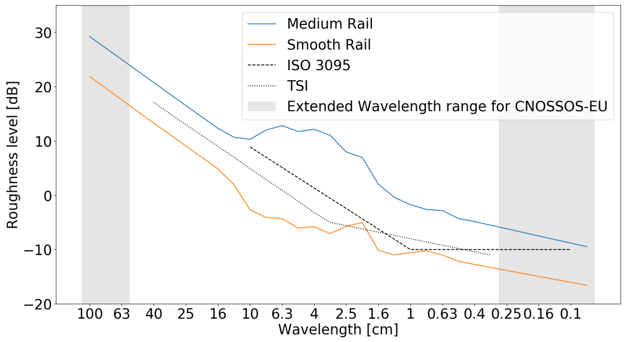

Figure 3: Rail roughness spectra of Järna2 (medium roughness rail) and Gårdsjö (smooth roughness rail) obtained from [13] and extrapolated, shown in comparison with ISO 3095 [11] and TSI limits [12]

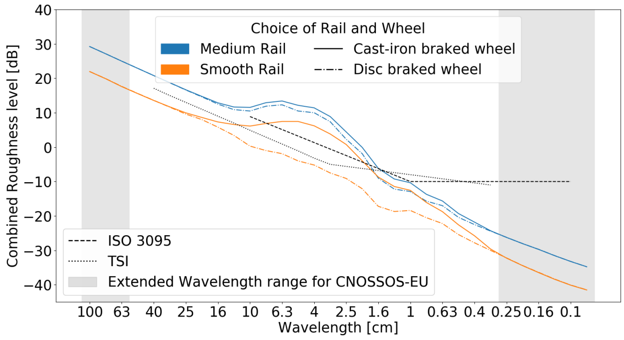

Figure 4: Combined roughness of Wheel spectra (Fig. 2), Rail spectra (Fig. 3) and baseline Contact filter for the 4 wheel-rail combinations shown in comparison with ISO 3095 [11] and TSI limits [12]

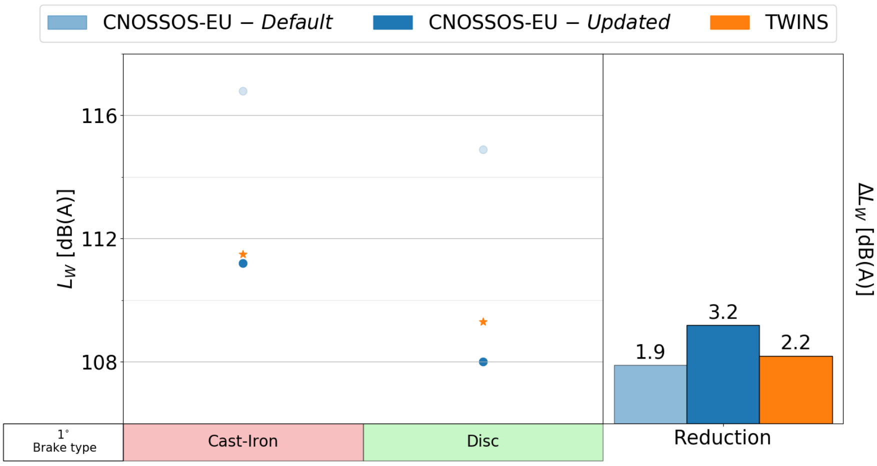

Figure 5: Evaluation of primary measure: change in brake technology. Left: Absolute SWL; Right: Reduction in L_W in dB(A)

by a switch from the *soft* rail-pads (baseline) to *hard* rail-pads. The track TFs corresponding to all three classes of rail-pads are presented in Fig. 9.

3.2 Default vs. Updated calculations with CNOSSOS-EU

This Section presents the A-weighted calculations from TWINS and CNOSSOS-EU for the test cases under consideration. For each case, the total SWL − L_W, is presented along with the reduction associated with the implementation of mitigation measures − ΔL_W, thus facilitating both an absolute and relative comparison. The CNOSSOS-EU output is post-processed as described in Section 2.2 in order to compare the results to those obtained with TWINS. The *default* and *updated* calculations in CNOSSOS-EU differ only by the choice of wheel and track TFs taken as input and the results are presented below. A discussion of the associated results is presented in Section 4.

3.2.1 Impact of primary measure

Fig. 5 shows the reduction in SWL when switching from Cast-iron brakes in the baseline configuration to Disc-brakes. The wheel roughness spectra used as input is shown in Fig. 2 and the wheel TFs for CNOSSOS-EU is shown in Fig. 8. Both configurations use the medium rail roughness in Fig. 3.

The reductions obtained by this primary measure are again shown in Figs. 6 and 7 for comparison with improvements associated with the secondary measures.

3.2.2 Impact of secondary measures

The improvements in SWL reduction with the secondary measure applied independently or in combination with the primary measure are presented below.

Fig. 6 shows the reduction in SWL when considering the secondary measure of rail grinding. The secondary measure is implemented by changing the input rail roughness in Fig. 3 from *Medium* to *Smooth* spectra.

Fig. 7 shows the reduction in SWL when considering the secondary measure of rail-pad stiffening. The secondary measure is evaluated by changing the default vertical rail-pad stiffness from 150 MN/m to 1000 MN/m. In TWINS, this is introduced by changing the material property of the rail-pad, which in effect also changes the modelled track decay rates, while in CNOSSOS-EU, this is done by changing the input track TFs in Fig. 9.

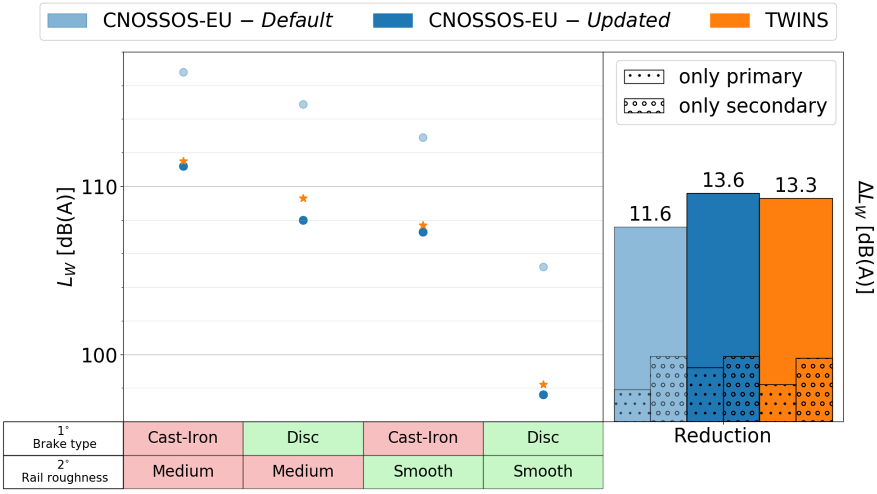

Figure 6: Evaluation of improvement with secondary measure: rail grinding. Left: Absolute SWL; Right: Reduction in L_W in dB(A)

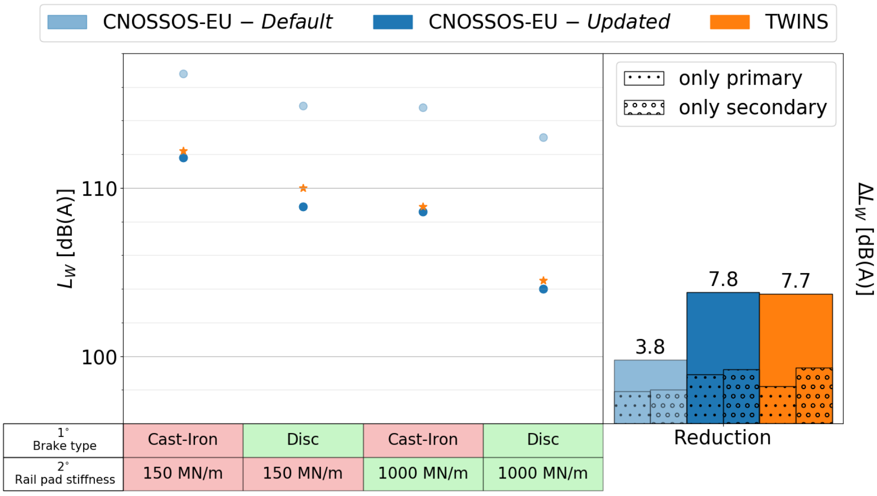

Figure 7: Evaluation of improvement with secondary measure: rail-pad stiffening. Left: Absolute SWL; Right: Reduction in L_W in dB(A)

3.3 Comparison of Transfer functions

The wheel and track TFs used for the CNOSSOS-EU calculations are shown in Figs. 8 and 9. The TFs from the *default* calculation are compared with those extracted from TWINS for the *updated* calculation. The frequency spectrum of the extracted TFs is limited to the output spectrum of TWINS, corresponding to the range 100 Hz - 5 kHz. A constant value extrapolation of the extracted TF is done in order to satisfy the input spectrum requirements of CNOSSOS-EU.

3.3.1 Wheel

Fig. 8 compares the default wheel TF for a generic shape 920 mm wheel with those extracted for curved and straight web geometry from TWINS results. As may be seen from Fig. 8, there is a clear difference between the default and extracted TFs, the former being consistently higher in magnitude across most of the spectrum. A distinction is also observed between a curved and straight web geometry, allowing the evaluation of the change in brake technology to also account for the impact from change in wheel geometry.

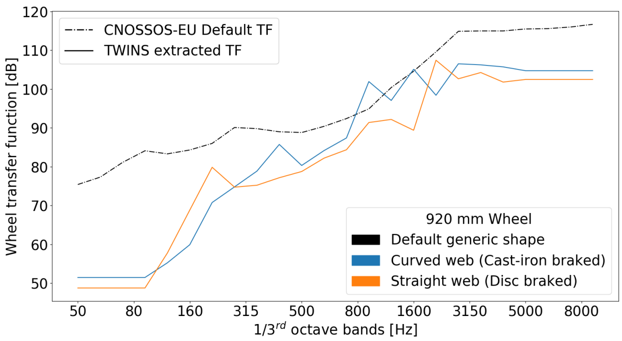

Figure 8: Default and extracted wheel TFs for 920 mm wheel profile

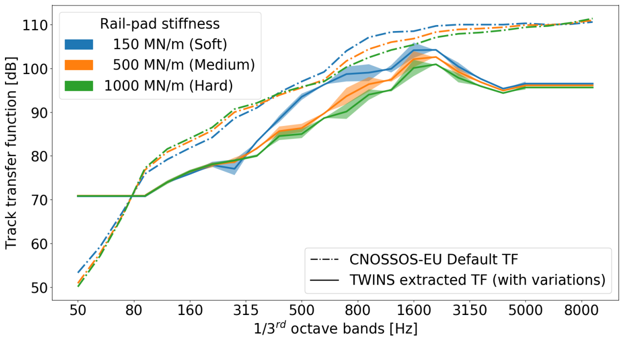

Figure 9: Default and extracted track TFs of a mono-block sleeper on 3 type of rail pads - Soft, Medium and Hard. Specifications of track component mentioned in Table 1

3.3.2 Rail

In this case study, a track TF is extracted using multiple distinct TWINS calculations which evaluate the same type of track. The TF finally used for the *updated* calculation is plotted as a solid-line with error-bars highlighting the limits of the TFs from the set of distinct calculations. Fig. 9 shows the track TFs for different rail-pad stiffness values. In Fig. 9 it is observed that the default track TFs are higher in magnitude than the extracted track TFs, similar to the wheel TFs in Fig. 8. The magnitude and orientation of change varies across the frequency bands between the default and updated TFs. The large discrepancy may be justified as partly due to the unclear origin of rail-pad stiffness values that describe the default TFs [14].

4 Discussion

TWINS is regarded as a standard for evaluating railway rolling noise [8] and is therefore considered as a target for reliable CNOSSOS-EU calculations. For each case with its respective input roughness spectra, the CNOSSOS-EU *default* and *updated* calculations show large variations in both absolute and relative assessments (see Figs. 5 - 7). The two sets of calculations under the different measures vary primarily in the choice of wheel and track TFs, highlighting the crucial influence of these TFs and the distinction between default and extracted values.

For all cases considered, the *default* CNOSSOS-EU calculation overestimates the absolute SWL by at least 4.5 dB(A) (*e.g.,* Disc braked wagon on a track without secondary measures in Fig. 5) and up to 8.5 dB(A) (*e.g.,* Disc braked wagon on a track with 1000 MN/m rail pads in Fig. 7) for the worst case. The reason for this may be associated with the wheel and track TFs: in Figs. 8 and 9, the default TFs are higher on average than the extracted TFs which reflect the dynamic behavior modelled by TWINS. In comparison, the *updated* calculation's absolute values vary by at most 1.3 dB(A) (freight wagon on a track without secondary measures in Fig. 5) for all considered configurations. It is interesting to note that the absolute SWL obtained with the *updated* calculation is a consistent underestimation, thus implying that the cause may well be a systematic bias in the extracted TFs.

In the relative assessment, the *default* calculation shows deviations of almost 4 dB(A) (*e.g.,* reduction from implementing both primary measure and rail-pad stiffening in Fig. 7), whereas deviation in the *updated* calculation is limited to 1 dB(A), which occurs for the evaluation of the primary measure (see Fig. 5). The cause for the *updated* calculation's 1 dB(A) overestimation in the relative assessment may be due to an overestimation of reduction in the track-component contribution, in comparison with TWINS's track-component.

5 Conclusion

Rolling noise source strength calculation using CNOSSOS-EU is seen to be significantly dependent on the choice of input values, namely – wheel and track transfer functions (TFs), implying good quality TFs are required for reliable calculations. An approach is presented to extract TFs for CNOSSOS-EU from TWINS calculations that utilizes similarities between their rolling noise calculation methodologies. It is applied to a test case developed to evaluate rolling noise mitigation measures on freight wagons on a railway network typical in Sweden. Rolling noise SWL calculations by TWINS are compared with two sets of CNOSSOS-EU calculations that differ in the origin of the track and wheel TFs: a *default* calculation using existing CNOSSOS-EU database, and an *updated* calculation using TFs extracted from TWINS results. The extracted TFs lead to CNOSSOS-EU calculation results that better matched that of TWINS calculations. Previous deviations of up to 8.5 dB(A) were reduced to 1.3 dB(A) for the absolute SWL calculations, and those up to 4 dB(A) were reduced to 1 dB(A) for the relative measure. The method also enables CNOSSOS-EU to evaluate changes to the system that are not possible with the default database of TFs, such as changing wheel geometry.

Despite the generality and simplicity of CNOSSOS-EU in comparison to TWINS, appropriate choice of input TFs obtained using the presented approach enables CNOSSOS-EU results to approach that of TWINS, highlighting its effectiveness. This allows for more reliable evaluation of railway rolling noise by CNOSSOS-EU, especially in the context of END strategic noise mapping.

Acknowledgements

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