Rail roughness and rolling noise in tramways

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Abstract. Companies which manage railway networks have to cope continually with the problem of operating safety and maintenance intervention issues related to rail surface irregularities. A lot of experience has been gained in recent years in railway applications but the case of tramways is quite different; in this field there are no specific criteria to define any intervention on rail surface restoration. This paper shows measurements carried out on some stretches of a tram network with the CAT equipment (Corrugation Analysis Trolley) for the principal purpose of detecting different states of degradation of the rails and identifying a level of deterioration to be associated with the need for maintenance through rail grinding. The measured roughness is used as an input parameter into prediction models for both rolling noise and ground vibration to show the potential effect that high levels of roughness can have in urban environment. Rolling noise predictions are also compared with noise measurements to illustrate the applicability of the modelling approach. Particular attention is given to the way the contact filter needs to be modelled in the specific case of trams that generally operate at low speed. Finally an empirical approach to assess vibration levels in buildings is presented.

1. Introduction

Railway rolling noise is generated by the vibrating wheels and rails and is induced by the roughness at the contact between the two. In cities served by trams, noise and vibrations are important reasons for nuisance and complaint. Tramlines are usually in close proximity to buildings so that noise can be easily perceived inside and vibration can easily propagate through the ground and into the rooms.

Furthermore, depending on the speed of the vehicle, on the form of the track, and on the distance from the source, vibration and noise can be perceived differently. Vibration in buildings is observable as whole body feelable vibration from 4 to 80 Hz and as reradiated noise between 20 and 250 Hz [1]. Airborne noise from railways can result in a wide range of frequecies, and normally for what concerns the wheel/rail interaction, the range of interest is between 100 and 5000 Hz [1].

The irregularities of the contacting surfaces induce dynamic interaction forces between the wheel and track, resulting in the excitation of various frequencies and so in the emission of noise and vibrations. The unevenness of the rail surface is normally quantified in decibels as a function of wavelength as:

$$L_r = 10\log_{10}\left(\frac{r_{rms}}{r_{ref}}\right)^2 \quad \textbf{(1)}$$

where r_{rms} is the root mean square value of the roughness measured over a certain distance within a certain wavelength band, while r_{ref} is the reference value, usually set to 1 μm. As long as the roughness level is below a certain limit [2] there is a linear correlation between radiated noise (and vibration level in the ground) and roughness.

To control noise, monitoring of roughness is used in some situations on mainline railways to trigger acoustic grinding of the rails. For example in Germany, the 'specially monitored track sections' are designated with a lower emission level because of this programme of acoustic grinding [3]. A limit curve for rail roughness of conventional rails is provided by the Technical Specification for Interoperability (TSI) [4], although this limit is intended for specifying a test track for testing new vehicles and does not apply to normal operation. However, for tramway rails, due to major differences between the configuration of each urban network, harmonization on this issue, into the international regulations, cannot be easily achieved.

The purpose of the work presented here is to determine a suitable limit curve for tramways using an indirect procedure, based on the simulation of noise and vibration from measured roughness data. The accelerometer-based instrument CAT (Corrugation Analysis Trolley) [5], was used in the campaign of measurements to detect the longitudinal profile of the rail surfaces. This instrument is in compliance with the latest requirements of the European regulation in force, specifically EN 15610 [6]. This roughness data is then used with a simulation model for rolling noise based on the TWINS model [7], [8]. In parallel a model is used for ground vibration [9], this was developed on the basis of the studies of Sheng et al. ([10], [11], [12]). It has been extended with simple empirical relations [13] to give estimates of ground-borne noise inside buildings. A comparison is then made between predicted levels and noise limits given by local regulations: a predicted noise level above the limit implies that the corresponding roughness is too high. This can give a good foundation to define a limit in roughness level and support the of infrastructure manager in defining a maintenance plan.

2. Measurements of roughness

During 2013-14 roughness was measured at a range of sites of a city's tram network in Italy utilizing a CAT trolley. The sites measured are listed in table 1 and are identified with a letter. One of the sites is shown in Figure 1. In most sections investigated it was necessary to clean the rail surface with a brush prior to the measurement to eliminate dust, debris and leaves and twigs from the groove of the rail. The running band was identified on the top of rail surface and the sensor was centred relative to this, as required in [6].

Each measurement section was 30 m long and selected in the critical zones where tram usually accelerates (or decelerates), i.e. near tram-stops or at traffic lights.

Table 1. Summary of measurements.

Test date/corrugation inspection	Name	Tram line
11 July 2013	C	3
04 February 2014	F	8
	G	8
	H	8
	I	8
18 March 2014	M	8
	N	8
	O	8
	P	8
08 April 2014	Q	2
	R	14
30 April 2014	S	8
22 May 2014	U	8
10 September 2014	V	3

Figure 1. Corrugated rail R, relating a straight section of the right track of a bidirectional line.

Data have been verified to check the presence of unwanted incongruous features [14]. The first and last 2.5 m of each measured sample have not been considered. Measurement data have been post-processed according to EN 15610:2009, spectra from which are shown in Figure 2 for six locations (I, N, M, Q and R). The results are all well above the limit curve provided in the TSI for railways, in some cases by more than 20 dB. The roughness spectrum of the rail with lowest roughness (M) has been fitted with a double slope line (labelled CS in Figure 2) following a trend similar to the one of the TSI limit curve. This CS line can provide a 'smooth' term of comparison for the other spectra.

For a tram speed of 30 km/h (8.3 m/s), the ground vibration frequency range of 4-80 Hz corresponds to wavelengths between 2 m and 100 mm, the ground-borne noise frequency range (20-250 Hz) corresponds to 400 mm to 33 mm while the frequency range of rolling noise (200-5000 Hz) corresponds to wavelengths between 40 mm and 1.6 mm. The minimum wavelength obtained in the measurements is 6.3 mm which corresponds to 1.25 kHz at 30 km/h. Therefore shorter wavelengths have been estimated by extrapolation of the spectra.

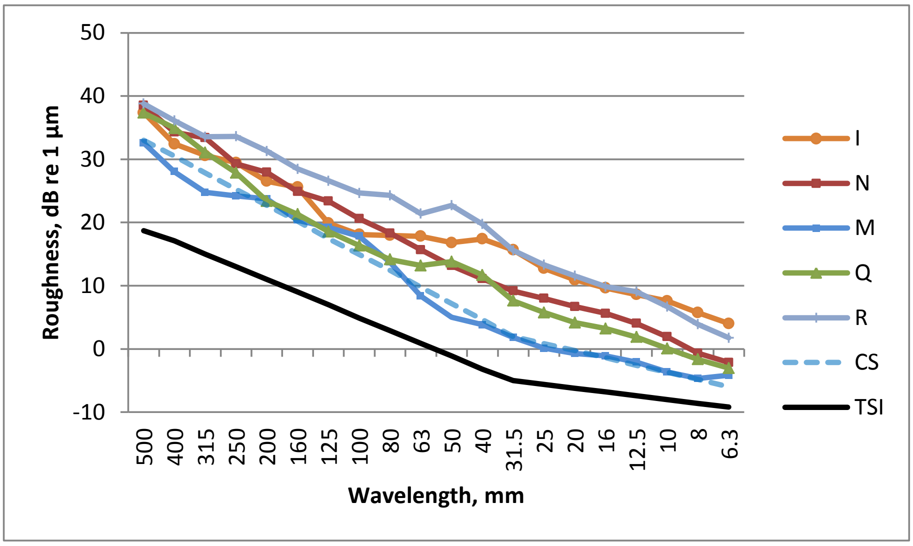

Figure 2. Measured roughness at different sections compared with limit curve from TSI [4] and smooth reference curve CS.

3. Airborne noise

3.1. Rolling noise

3.1.1. Modelling. An existing software has been used to predict noise level from measured roughness. This software, called STARDAMP, implements calculations based on the same theory as TWINS [7], [8] in an easy-to-use way. Although this software was developed in the STARDAMP project [15] to assess the effect of rail and wheel dampers it is here used as a convenient way to predict noise levels. An example simulation is given in Figure 3, where the A-weighted sound pressure level (SPL) is presented as the sum of the SPL of the wheel and of the track. The noise prediction in this case corresponds to a distance of 2.25 m from the track centreline and a height of 1.2 m above the top of rail. A calculated track decay rate is taken into account in the simulations.

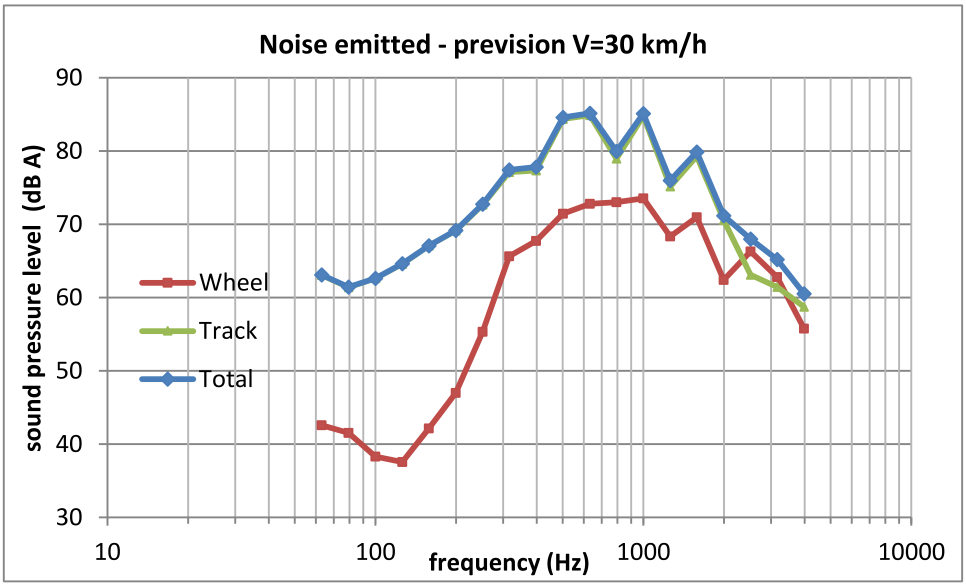

Figure 3. Total Sound Pressure Level at 2.25 m x -1.2 m, dBA.

In the STARDAMP software the tram was modelled in terms of the wheel modal basis obtained from a finite element model. Wheel roughness is neglected as this is expected to be much lower than the rail roughness. As an example of the standard track design of this city a ballasted track with wooden sleepers is defined; low stiffness is considered for rail pads corresponding to 100 MN/m.

3.1.2. Measurements. In order to validate the use of the software, a comparison with measured noise is presented for one of the investigated areas. In particular, measurements of noise were carried out on a straight stretch of track between two tram stops of one of the network's tram lines surveyed. The rail was visibly corrugated (Figure 1), with a predominant wavelength of 5 cm: the acoustic roughness spectrum recorded in situ is the one named R in Figure 2. The microphone was located at 7.5 m from the centre of the track and 1.2 m above the ground. The overall noise obtained from the recordings, limited to the time which the tram is passing-by, is given in Table 2. The average noise level is 89.8 dBA. These results will be compared with the simulations in the next section.

Table 2. Overall noise measured in situ.

Recording	Overall noise (dBA)
1	87.6
2	87.2
3	87.3
4	90.3
5	88.0
6	91.7
7	92.8

3.1.3. The contact filter. An adaptation of the software was needed to model the tram situation as it has a lower load and reduced speed compared with the mainline railway. In particular, considering the low running speed of trams, the way contact filter is modelled becomes important as smaller wavelengths are required than for typical train speeds. The contact between rail and wheel takes place over a certain elliptical area of dimensions $2a \times 2b$; wavelengths shorter than the contact area tend to be attenuated. This phenomenon is called the contact filter. Often it is modelled using the so called Remington formula ([16]). The blue line in Figure 4 identifies Remington filter and is given by:

$$\left|H^2(k)\right| = \left(1 + \frac{\pi}{4}(ka)^3\right)^{-1} \quad (2)$$

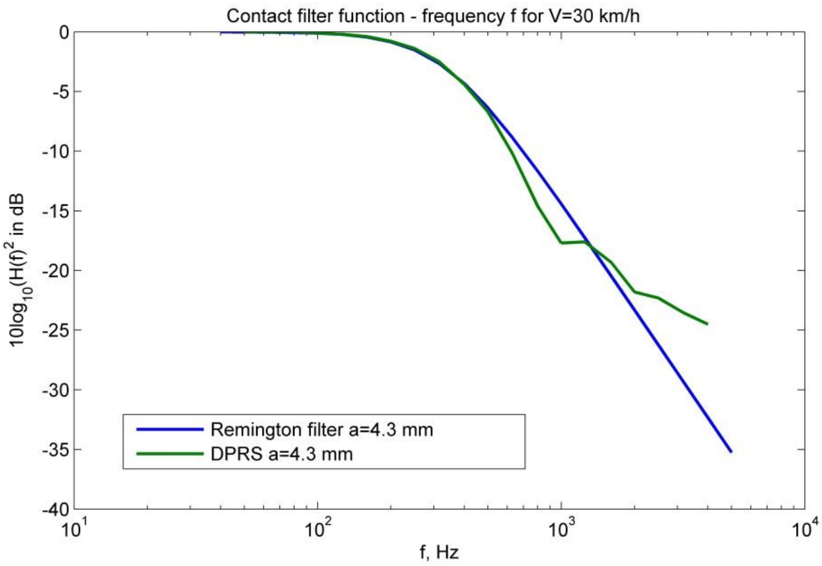

Figure 4. Blue: simplified Remington filter with *a*=4.3 mm; green: *DPRS* corresponding to *a=4.3mm* (V=30km/h).

A more sophisticated numerical model also exists that represents the surfaces in contact with distributed-point-reacting-springs (DPRS, [17]). For a train speed of 30 km/h the two approaches show similar results up to 500 Hz, while there are significant differences above this (see Figure 4). The DPRS result from [1] has to be corrected for the shorter contact patch length in the present case. Finally, the difference between the Remington filter model and DPRS model result is applied to the STARDAMP results as a correction to the SPL spectrum.

Figure 5 shows a comparison of the predicted SPL with the range of measured spectra. Acceptable agreement is found, with the simulations falling within the range of the measurements. It is clear that the DPRS contact filter gives a better result at high frequencies than the Remington formula.

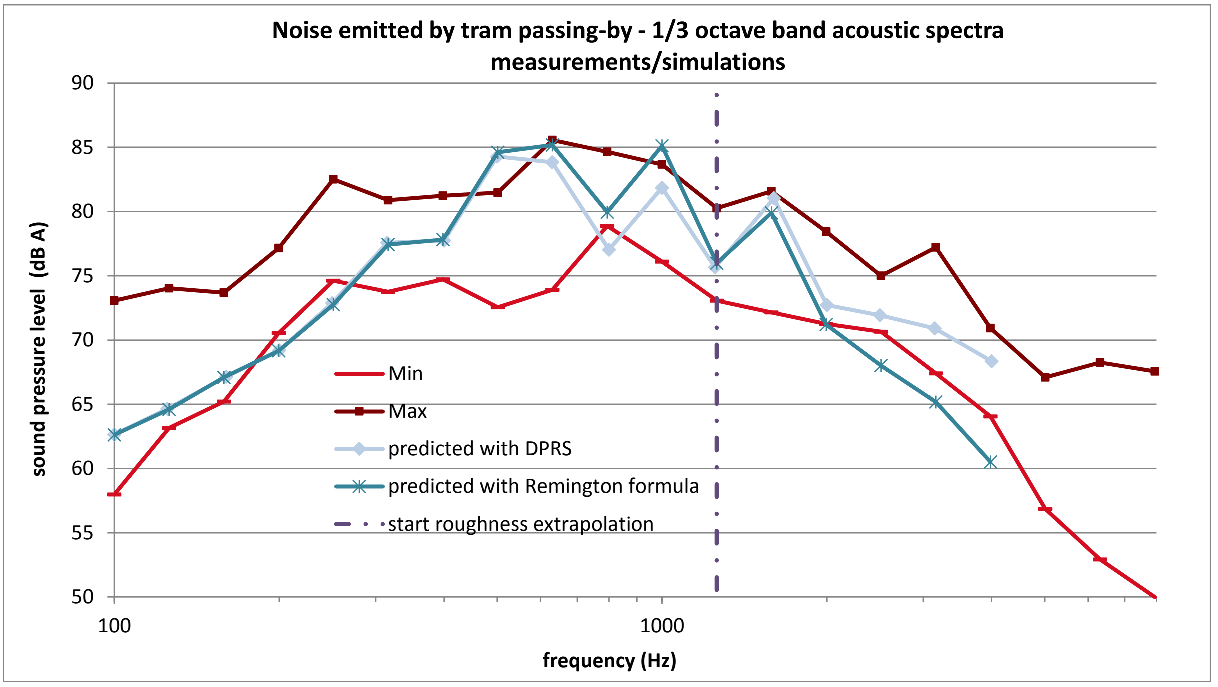

Figure 5. Comparison of predicted and measured SPL from tram pass-by.

3.2. Noise Maps

Regulations in the cities provide “noise maps" (acoustic zoning), which are the result of the acoustic zoning plans for the noise assessment in the environment.

Figure 6. Extract of the Noise Map of the city. Green: Class I 50 dB(A) day time; 40 dB(A) night time. Ivory: Class II 55 dB(A) day time; 45 dB(A) night time. Orange: Class III 60 dB(A) day time; 50 dB(A) night time. Brown: Class IV 65 dB(A) day time; 55 dB(A) night time. Lilac: Class V 70 dB(A) day time; 60 dB(A) night time. Blue: Class VI 70 dB(A) day and night time.

In the city where the study is carried out for example, since 2002, an acoustic zoning map is in force, an extract of which is given in Figure 6. Each different colour used in this map belong to the corresponding territorial class, with different limits for equivalent level noise Leq in dB(A). These limiting values apply to the total noise in a zone. A more stringent limit value is provided in the DPCM 14/11/97 [18] regarding the emission of single sources of noise which should each remain 5 dB below the overall limit.

3.3. Noise at several distances

To show examples of the methodology, four locations have been selected, corresponding to different zones in Figure 6. In each case the roughness has been measured. A typical receiver distance is selected based on the distance from the tram tracks to the nearest buildings. These cases are listed in Table 3, with the receiver distance and roughness location. The column “Limit” lists the immission limit allowed in each area as indicated in the Noise Map. The limit value provided in the DPCM 14/11/97 [18] for single sources of noise is listed as the “Tram limit” in Table 3.

The STARDAMP code is used with the corresponding roughness spectrum to determine the SPL during the passage of a single tram. Then, taking into account the frequency of tram passages in that area during daytime and nighttime, the equivalent level of noise L_{eq} for each situation is determined. This value is comparted with the limit value for that specific area.

The noise immission into the environment satisfies the limit with the CS rail roughness in the ‘brown’ area. However, the other cases analyzed, which have higher rail roughness, exceed the corresponding thresholds by between 10 and 15 dB. For this reason, the calculations have been repeated using the CS roughness curve, as shown in Table 4. Even in these cases the limits are exceeded. However, as the model is linear, it is possible to deduce the level that would be obtained by maintaining the same spectrum shape as the CS curve but lowering it by a constant amount. Thus to respect the Leq limit in the environment for the ‘orange’ location, the roughness has to be 3 dB lower than the CS curve. Similarly in the ‘green’ zone (the areas which are ‘very protected’, such as hospitals, schools…) a roughness curve 10 dB below the CS curve is required. The final case is a zone where the buildings are very close to the tracks. Here, even though the noise limits are identical to the ‘brown’ zone, the roughness should be 8 dB below the CS curve.

If the same calculations are made with the TSI reference curve proposed in the railway field, the standard is respected in the brown and orange zones. For the green zone even the TSI curve is not sufficient to meet the demands of the standard. In this case good rail grinding is not enough, and a passive noise protection system is needed in addition.

Table 3. Comparison of predicted noise with zonal limits for measured roughness.

	Distance (m)	Roughness (name)	STARDAMP prediction (dBA)	Leq (dBA)	Limit (dBA)	Tram limit (dBA)	Exceedance (dBA)
Day brown	20	CS	**74.6**	**59.2**	65	60	-0.8
Night brown	20	CS	**74.6**	**49.5**	55	50	-0.5
Day orange	20	I	85.4	68.2	60	55	13.2
Night orange	20	I	85.4	58.3	50	45	13.3
Day green	60	N	75.2	59.8	50	45	14.8
Night green	60	N	75.2	50.1	40	35	15.1
Day very close	2.25	Q	85.9	70	65	60	10
Night very close	2.25	Q	85.9	61.5	55	50	11.5

Table 4. Comparison of predicted noise using CS roughness with zonal limits.

Adjusted to CS roughness								
	Distance (m)	Roughness (name)	STARDAMP prediction (dBA)	Leq (dBA)	Limit (dBA)	Tram limit (dBA)	**Exceedance (dBA)**	**Required limit curve**
Day brown	20	CS	**74.6**	59.2	65	60	**-0.8**	**CS**
Night brown	20	CS	**74.6**	49.5	55	50	**-0.5**	**CS**
Day orange	20	CS	**74.6**	57.4	60	55	**2.4**	**CS-3**
Night orange	20	CS	**74.6**	47.5	50	45	**2.5**	**CS-3**
Day green	60	CS	**69.6**	54.2	50	45	**9.2**	**CS-10**
Night green	60	CS	**69.6**	44.5	40	35	**9.5**	**CS-10**
Day very close	2.25	CS	**82**	66.1	65	60	**6.1**	**CS-8**
Night very close	2.25	CS	**82**	57.6	55	50	**7.6**	**CS-8**

Two limit curves for tram roughness are proposed in Figure 7. According to the above results, these will satisfy the Italian standard for emission of noise in the 'brown' (CS) and 'orange' (CS–3 dB) zones.

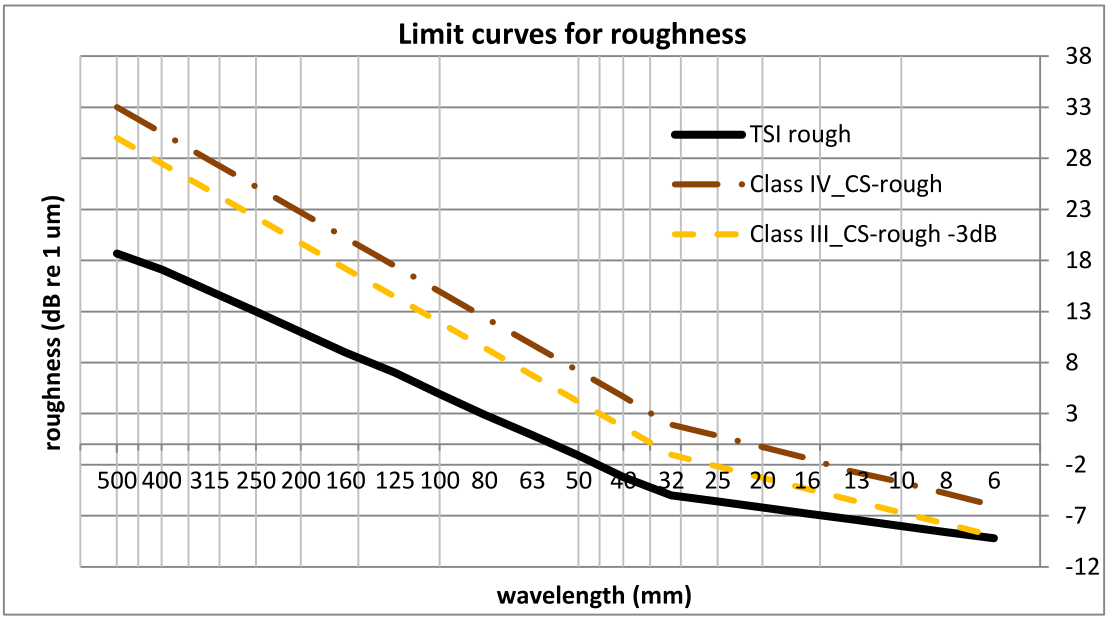

Figure 7. Roughness limit curves per area.

4. Ground vibration

4.1. Ground vibration model

A similar procedure has been followed for the ground vibration. A semi-analytical model called TGV (Train-induced Ground Vibration) is used [9]. In this model the vehicle is represented as a multi-body model with primary and secondary suspension. For the particular case studied a 16 degree of freedom (DOF) vehicle model was implemented including three bogies and two car bodies. The track is represented as an infinite beam on layers of springs and masses connected to a layered elastic ground. The analysis is undertaken in the wavenumber domain with a Fourier transform used to transform the results back from the wavenumber domain to the spatial domain. The model includes both the moving quasi-static loads and the dynamic loads due to roughness but at any distance away from the track it is the latter which dominates. Results are predicted as the average velocity spectra at different distances from the track during the tram passage.

4.1.1. Vibration into buildings. To determine the ground vibration levels within buildings different stages are followed, as proposed in [13]. Starting from the free-field vibration calculated using TGV, an attenuation is first applied to allow for the soil-structure interaction, leading to an estimate of the vibration at the foundation of the building. For common buildings, for example 2- to 4-storey masonry buildings on spread footings, this attenuation is in the range -5 to -13 dB between 10 and 30 Hz. Next a transfer function is applied allowing for the attenuation of vibration up the building. A third transfer function is used to estimate the amplification between the walls and the middle of the floor of a room. Finally the weighting curve specified in UNI 9614 (z axis) is applied to the vibration spectrum and the spectrum is integrated to give a single number assessment of the vibration level that can be compared with the standard.

4.1.2. Noise inside buildings. Once the vibration reaches the floors and walls of the buildings, the noise radiated from them can be estimated using the Kurzweil formula

$$L_{pi} = L_v\left(\text{dB } re\, 10^{-9}\ \text{m/s}\right) - 27 \quad \textbf{(3)}$$

where L_{pi} is the SPL (in dB re 20 μPa) inside the room, and L_v is the vertical velocity level of vibration in dB re 10^{-9} m/s. Finally the SPL is expressed as an A-weighted level.

4.2. Limits for feelable vibrations and noise in buildings

The human exposure to whole-body vibration into buildings is regulated in Italy by UNI 9614:1990 [19] based on the standard ISO 2631- part 2 [20]. The standard provides limits, in terms of frequency-weighted acceleration (and the corresponding vibration levels in dB), for vertical and horizontal direction. Table 5 reports these limit values of acceleration and corresponding level in dB for different building uses.

Table 5. Limit values for weighted acceleration.

Italian Standard: UNI-9614				
	z-axis		x-/y-axis	
Area	a_w (mm/s^2)	L_{aw} (dB re 10^{-6} m/s^2)	a_w mm/s^2	L_{aw} (dB re 10^{-6} m/s^2)
Critical Areas	5	74	3.6	71
Residential (Night)	7	77	5	74
Residential (Day)	10	80	7.2	77
Offices	20	86	14.4	83
Industrial	40	92	28.8	89

This standard, however, does not take into account radiated sound. In this paper, this will be compared with the American guideline limits [21], in Table 6.

Table 6. Criteria and design goals for maximum groundborne noise from train operations.

Maximum Pass-by Ground borne Noise Level			
Community Area Category	Single	Multi	Hotel

	family dwellings (dBA)	family dwellings (dBA)	motel (dBA)
Low –density residential	30	35	40
Average residential	35	40	45
High –density residential	35	40	45
Commercial	40	45	50
Industrial/highway	40	45	55

4.3. Results

Figure 8 shows the vibration spectra at the ground surface predicted the TGV model for a roughness based on the CS curve. Applying the various transfer functions described in Section 4.1.1 leads to a weighted vibration level of 84.6 dB for a building at 15 m from the track. This can be compared with the limits in Table 5, showing that the vibration is above these limits for residential buildings.

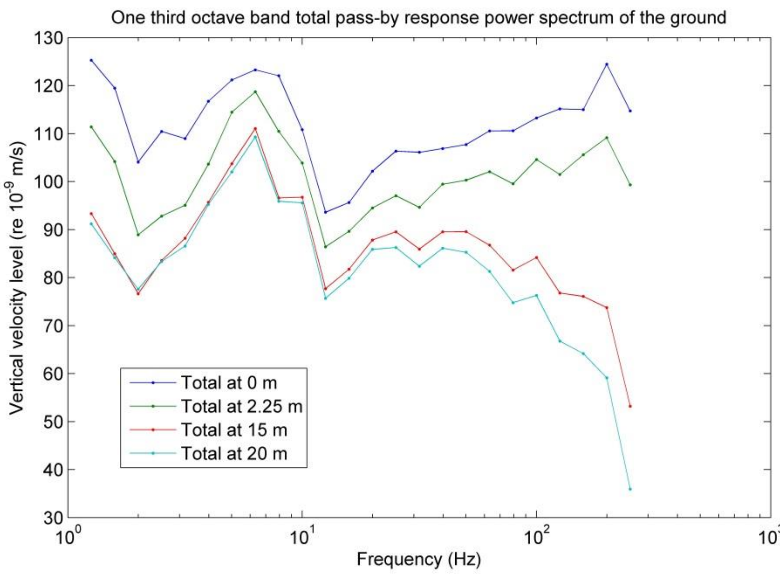

Figure 8. Vertical velocity level at different distances predicted using TGV model with 16 DOF vehicle.

Concerning the ground borne noise, the predicted value in a building at 15 m from the track for the CS roughness curve is 34.5 dBA. This is below the limit provided by the American guidelines provided by the Federal Transit Administration in [21] for residential buildings (Table 6).

5. Conclusion

A procedure has been demonstrated to estimate noise and vibration levels from tram operations based on the measured rail roughness. Comparing these estimates with limits for noise and vibration allows a limit curve for the roughness to be proposed that would allow the noise limits for the particular areas studied to be respected.

The proposed maximum levels of roughness provide a useful support in deciding the timeline for grinding the rails. In other words, it will be advised to grind the rails as **immediate action** whenever the emission predicted will be over a certain level of acceptance in terms of noise or vibration. The proposed roughness limit curves are challenging. For sensitive areas it is recognized that additional noise mitigation may be necessary to meet the environmental noise criteria.

References

[1] D. Thompson, *Railway noise and vibration: mechanisms, modelling and means of control*. Elsevier Science, 2008.

[2] D. J. Thompson, "On the relationship between wheel and rail surface roughness and rolling noise," *J. Sound Vib.*, vol. 193, no. 1, pp. 149–160, May 1996.

[3] B. Asmussen, H. Onnich, R. Strube, L. M. Greven, S. Schröder, K. Jäger, and K. G. Degen, "Status and perspectives of the 'Specially Monitored Track,'" *J. Sound Vib.*, vol. 293, no. 3, pp. 1070–1077, 2006.

[4] TSI, "Commission Regulation (EU) No 1304/2014 of 26 November 2014 on the technical specification for interoperability relating the subsystem 'rolling stock – noise' amending Decision 2008/232/EC and repealing Decision 2011/229/EU. Official Journal of the European Union L356/421-437." 2014.

[5] S. L. Grassie, "Rail corrugation: advances in measurement, understanding and treatment," *Wear*, vol. 258, no. 7–8, pp. 1224–1234, Mar. 2005.

[6] EN 15610:2009, "EN 15610: 2009 Railway applications. Noise emission. Rail roughness measurement related to rolling noise generation." EN 15610: 2009, 2009.

[7] D. J. Thompson, B. Hemsworth, and N. Vincent, "Experimental validation of the twins prediction program for rolling noise, part 1: description of the model and method," *J. Sound Vib.*, vol. 193, no. 1, pp. 123–135, May 1996.

[8] D. J. Thompson, P. Fodiman, and H. Mahé, "Experimental validation of the twins prediction program for rolling noise, part 2: results," *J. Sound Vib.*, vol. 193, no. 1, pp. 137–147, May 1996.

[9] E. Ntotsios, S. Koroma, W. Hamad, D. J. Thompson, H. Hunt, J. Talbot, and M. F. M. Hussein, "Modelling of train-induced vibration," presented at the The Stephenson Conference, IMechE, London, UK, 21-23 April 2015.

[10] X. Sheng, C. J. C. Jones, and M. Petyt, "Ground vibration generated by a harmonic load acting on a railway track," *J. Sound Vib.*, vol. 225, no. 1, pp. 3–28, Aug. 1999.

[11] X. Sheng, C. J. C. Jones, and M. Petyt, "Ground vibration generated by a load moving along a railway track," *J. Sound Vib.*, vol. 228, no. 1, pp. 129–156, Nov. 1999.

[12] X. Sheng, C. J. C. Jones, and D. J. Thompson, "A theoretical model for ground vibration from trains generated by vertical track irregularities," *J. Sound Vib.*, vol. 272, no. 3–5, pp. 937–965, May 2004.

[13] P. M. Nelson, *Transportation noise reference book*. London: Butterworth, 1987.

[14] L. Chiacchiari and G. Loprencipe, "Measurement methods and analysis tools for rail irregularities: a case study for urban tram track," *J. Mod. Transp.*, pp. 1–11, Apr. 2015.

[15] G. Squicciarini, M. G. R. Toward, and D. J. Thompson, "Experimental procedures for testing the performance of rail dampers," *J. Sound Vib.*, vol. 359, pp. 21–39, Dec. 2015.

[16] P. J. Remington, "Wheel/rail noise—Part IV: Rolling noise," *J. Sound Vib.*, vol. 46, no. 3, pp. 419–436, Jun. 1976.

[17] P. Remington and J. Webb, "Estimation of wheel/rail interaction forces in the contact area due to roughness," *J. Sound Vib.*, vol. 193, no. 1, pp. 83–102, May 1996.

[18] "DPCM 14.11.97 - Determinazione dei valori limite delle sorgenti sonore." .

[19] "UNI 9614:1990 - Misura delle vibrazioni negli edifici e criteri di valutazione del disturbo." Ente Nazionale Italiano di Unificazione.

[20] "ISO 2631-2:2003 - Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 2: Vibration in buildings (1 Hz to 80 Hz)." International Organization for Standardization, 14-Apr-2003.

[21] C. E. Hanson, D. A. Towers, and L. D. Meister, "Transit noise and vibration impact assessment," Federal Transit Administration, FTA-VA-90-1003-06, May 2006.