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A survey on roughness measurements

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Abstract

The importance of well-defined rail and wheel roughness measurement methods has increased considerably since roughness limits have become part of type testing specifications (2001) and Technical Specifications for Interoperability (TSIs, 2002). Also, the European interim model (RMR) for railway noise predictions (2002) provides a method to correct measured noise emission by using the difference between the reference roughness and the measured roughness. Looking at the future, it can be expected that accurate assessment of roughness will become a standard requirement, as the Harmonoise method, which is intended to become the standard noise prediction method in Europe, uses the roughness spectrum as main input data for rolling noise. With these developments in mind, it is time to review what a decade of roughness measurements has achieved in terms of instrumentation, measurement procedures and analysis methods.

Ten years of experience using various roughness measurement systems lay at the basis of this paper. Directly measured (using a sensor) and indirectly measured (using a train) roughness results are compared. Over the years, the need to specify and approve measurement equipment has grown. A preliminary suggestion for standardisation is proposed and discussed. This will include a standard graphical representation and units for roughness. Average and spread of rail roughness and typical wheel roughness patterns are discussed. A separate section deals with rail roughness growth and grinding results. With regard to grinding as a noise reduction measure (so-called acoustical grinding), it is made clear that roughness monitoring is required to maintain the acoustical qualifications.

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1. Introduction

1.1. Roughness and rolling noise

Rolling noise is the noise from the vehicle and the track that occurs when the vehicle rolls on the rails. Irregularities (roughness) on the wheel tread and the rail head cause vibrations within the vehicle and the track that lead to the generation of noise. It has been demonstrated that the level of roughness is proportional to the generated rolling noise levels [1,2].

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1.2. Relevance for noise legislation

The notion that rail and wheel roughness directly influence rolling noise led to increased study of the phenomenon during the 1980s and 1990s by the European railway administrations (ERRI C163 and D185 projects). Accurate measurement equipment has been developed [3–5]. Also, the European Commission recognised the importance of gaining knowledge of and finding solutions for roughness generation and growth, through sponsorship of research projects like EuroSabot (wheel roughness) and Silent Track (rail roughness).

Eventually, roughness was introduced into European legislation. The Technical Specification for Interoperability (TSI) for high-speed rolling stock [6] refers to the draft standard prEN ISO3095 for type testing of trains [7] in which a measurement procedure and a limit spectrum for rail roughness are presented. This technical specification implies that the roughness level at the test sites where noise emission is measured should be below a certain limit level. Besides the TSI, the interim model for railway noise predictions European interim model (RMR) [8], which is referred to in the Environmental Noise Directive of the European Commission [9], requires roughness measurements in conformity with prEN ISO3095. In addition to this, a rail roughness correction method is given in RMR. The draft standard, the TSI limits and the noise computation methods are discussed here in more detail.

1.2.1. The type testing standard ISO3095

When in the 1990s it was considered that roughness measurement should be an essential part of the revised ISO3095, roughness measuring practice was still in its infancy. The measurement specifications (Annex D of this draft standard) were based on state of the art static roughness equipment capable of measuring profile samples of 1.2 m length. The specified procedure appears to be a compromise between the desire to keep the measurement time short and the need to provide a site average that takes into account the lateral variation of roughness across the rail head and the relative distance between the central microphone and the sections. The measurement procedure has been criticised during the Parallel Inquiry phase for this standard on many aspects [10], most of them related to the representativeness and accuracy of the resulting roughness spectra. Changes have been proposed [11], but a great difficulty remains, the lack of a standard to assess precision of the measuring instruments.

1.2.2. Technical specifications for interoperability

When the TSI for high-speed rolling stock came into force (2002), it was recognised that some track features could have a considerable effect on the measured noise emission of the rolling stock. Solutions for this situation have been explored by the Association pour l'Interopérabilité Ferroviaire (AEIF) in the NOEMIE project. An attempt was made to specify stringent but realistic limits for rail roughness and other track features that influence the noise emission of the high-speed trains.

NOEMIE was perhaps the first international project to encounter the oddities of prEN ISO 3095. The lack of a standard to assess the precision of the roughness measuring equipment led to exclusion of accelerometer-based trolley measurement systems during the measurement campaigns. Although prEN ISO3095 mentions the need to remove pits from the measured profile signals, it does not specify a method. Therefore, NOEMIE had to test available methods and approved three of them [12].

Another problem, not addressed by NOEMIE, is how to obtain the roughness level at long wavelengths in an accurate way. The use of 1.2 m based roughness instruments implies that only wavelengths shorter than about 10 cm can be determined accurately enough. As a result of not specifying a method, the different measurement teams in the project were free to invent and apply their own method for obtaining long wavelengths.

1.2.3. Noise computation methods

The RMR for railway noise computations [8] provides a method to correct measured noise emission by using the difference between the reference roughness and the actual roughness at the test site. The correction spectrum is given by

$$L_{\mathrm{correction}}(f) = (L_{R,\mathrm{rail,test}}(f) \oplus L_{R,\mathrm{wheel}}(f)) - (L_{R,\mathrm{rail,ref}}(f) \oplus L_{R,\mathrm{wheel}}(f)), \tag{1}$$

where $L_{R,\mathrm{rail,test}}$ is the average rail roughness spectrum of the test site, $L_{R,\mathrm{rail,ref}}$ is the reference rail roughness spectrum, $L_{R,\mathrm{wheel}}$ is the average wheel roughness spectrum of the test vehicle, f is frequency, given by train speed divided by roughness wavelength ($f = V/\lambda$) and $\oplus$ is energy summation. This correction spectrum is then subtracted from the measured noise spectrum.

The EU Harmonoise project has developed a noise prediction method that is intended to become the standard in Europe after 2007 [9]. Its railway noise model consists of several noise sources (rolling, traction, aerodynamic, etc.) of which the rolling noise contribution is calculated using the rail and wheel roughness spectrum as main input data [13]. The input values of rail and wheel roughness will therefore directly determine the calculated source power.

It is considered that the wheel roughness depends largely on the braking system of the rolling stock. By determining an average value for each type of braking system (e.g. cast-iron blocks, sinter blocks, disc brakes), a practical and reasonably accurate way is proposed to obtain input values for each type of rolling stock.

For rail roughness, the situation is different. Rough and smooth spots, causing noise differences of up to 15 dB [14], can alternate on a single track without corresponding changes in track components. Knowing this, there are two basic options for dealing with this variation in prediction models [15]:

1. Using an *average* rail roughness spectrum for the network. The consequence of this approach is that the calculated noise may deviate considerably from the actual noise at smooth or corrugated track sections.
2. Using *measured* roughness per section of track, by monitoring roughness regularly. This reduces the deviations in the prediction model to reasonable values, but the price for this accuracy is high: apart from monitoring, also the database with source data and hence the calculations have to be updated regularly.

Option 1 can still give a fair accuracy if a special grinding regime is applied, see also Section 4.3. For the purpose of noise mapping, option 2 is rather impractical.

2. Roughness measurements

2.1. Measurement purposes

Measurement of rail roughness (or wheel roughness) is required for at least four domains of application, each with their own requirements for measurement speed and accuracy:

A. Rail (or wheel) roughness of a test site (or test train). Examples: to assess noise emission, to study the effect of noise measures, to support type testing measurements (ISO3095).
B. Acceptance of grinding work (only rail roughness) [16].
C. Roughness as input in prediction models (Harmonoise).
D. Monitoring of roughness growth. Examples: to investigate causes and speed of growth, to identify the track sections and moment of intervention for rail grinding (or wheel reprofiling).

The desired accuracy and also the measurement quantity can be quite different between the areas of roughness expertise that correspond to these purposes. Basically, the track maintenance specialists, who are active in domains B and D, describe roughness in terms of amplitudes (mm or μm) and they divide the wavelengths from 10 to 1000 mm into four ranges. The railway noise specialists, who are active in domain A, C and D, speak about decibels relative to 1 μm RMS amplitude, while the wavelengths are divided into one-third octave bands ranging from 31.5 cm down to 0.5 cm or less. As acoustical grinding (Section 4.2.) is gaining interest, roughness measurements in domain B are becoming important for noise specialists as well.

In view of the range of applications of roughness measurements, it is not surprising that many different methods have been developed to assess roughness. These methods are explored in the next sub-section.

2.2. Measurement methods

Rail and wheel roughness can be measured in several ways. The measurement methods can be divided into *direct* and *indirect* methods.

Direct method: a measurement procedure in which the rail and wheel surface are scanned directly and independently from each other. The most frequently used systems apply displacement transducers or accelerometers in sensors that touch the rail or wheel surface. Several types of instruments have become commercially available since 1990 [3–5].

Indirect method: a measurement procedure in which the total effective roughness of rail and wheel is determined. Indirect measurements are carried out either on-board a running train (using axle-box accelerometers [17] or microphones [18,19]), or at a track site by measuring rail vibrations during train pass-bys [20].

Direct methods measure rail and wheel roughness independently, which is interesting for the many cases in which rail and wheel roughness are considered separately. Indirect methods do not yield separate rail and wheel roughness spectra. However, if one of both spectra is known or can be estimated, the other can be assessed via subtraction (and correction for contact filtering). An advantage of indirect methods is that they measure the actual roughness 'felt' by the wheel/rail contact, hence the roughness excitation itself. Direct methods have limited accuracy in determining the total effective roughness due to the uncertainty in the wheel/rail contact filter (CF) effect.

The relation between direct and indirect roughness measurements is obvious from a theoretical point of view. The energy summation of a directly measured rail roughness spectrum ($L_{R,\mathrm{rail}}$) and a directly measured wheel roughness spectrum ($L_{R,\mathrm{wheel}}$) yields the total roughness spectrum. In order to calculate the roughness excitation spectrum felt through the wheel/rail contact patch ($L_{\mathrm{tot,eff}}$), a CF must be applied. Therefore, the following rule applies

$$L_{\mathrm{tot,eff}} = (L_{R,\mathrm{rail}} \oplus L_{R,\mathrm{wheel}}) + \mathrm{CF}. \tag{2}$$

Typical CF spectra are calculated in Ref. [21]. Eq. (2) can be applied to find the unknown variable (if the three others are known). However, as the accuracy of the known quantities is generally fair but not high, the accuracy of the unknown quantity can be poor. This is illustrated in the following example.

Fig. 1 shows the calibration results of the axle-box measurement system described in Ref. [17]. The output signal of this system, that is attached to an unbraked wheelset of a measuring coach, is analysed into one-third octave band spectra. A speed-dependent transfer function is then applied to these acceleration spectra,

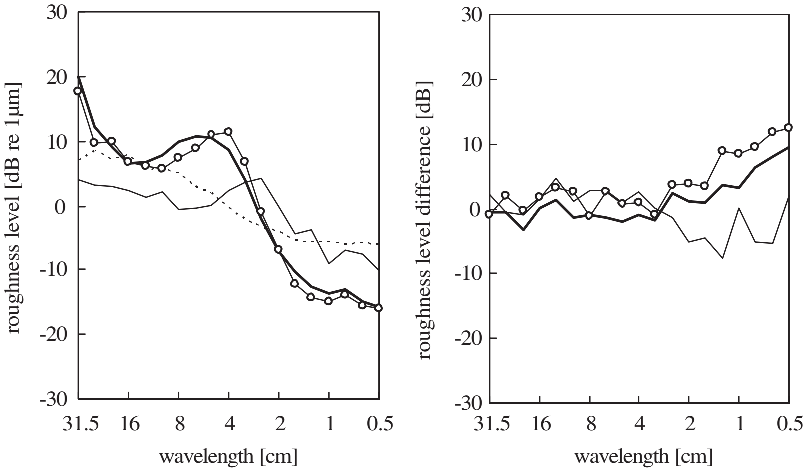

Fig. 1. Comparing indirectly to directly measured roughness: (a) rail roughness from 3 sites, measured with an RM1200E instrument, and the wheel roughness of a measurement coach, measured with an RMR1435 instrument. (b) Difference between the indirectly measured rail roughness (from the axle-box system of the measurement coach) and the directly measured rail roughness (from the RM1200E). — Site 1; ▬ Site 2; ○ Site 3; ---- Wheels.

rendering total roughness $L_{\mathrm{tot,eff}}$. With Eq. (2), using the directly measured wheel roughness $L_{R,\mathrm{wheel}}$, the rail roughness is calculated. The right-hand graph shows the difference between the rail roughness results of the axle-box system and the RM1200E instrument. It can be seen that the results are quite similar for wavelengths longer than 3 cm, where the wheels are smoother than the track. Large deviations occur for the shorter wavelengths.

2.3. Requirements for a measurement procedure

Due to the variety of purposes and the needs in terms of accuracy, wavelength range and track length, it is not desirable to design one single roughness measurement procedure that suits all applications. Instead, it is proposed first to define a set of general qualitative requirements and secondly to refine or quantify these requirements for the different domains of application. The second step is left for future work.

The measurement procedures should at least consider the following requirements for the different domains of application:

- the roughness quantity to be presented
- the wavelength range in which the roughness quantity is determined
- the required accuracy
- the (graphical) presentation of the results

Furthermore, the procedure should

- be independent of the instrument used
- be practical
- cope with lateral variation (e.g. two running bands or one wide running band)
- be representative
- leave no subjective choice and avoid improvisations

2.4. Requirements for measurement equipment

For a well-defined, reproducible, instrument-independent measurement result, it will not be sufficient to develop only procedures for measurement and analysis. There is a growing need to specify and approve the measurement equipment due to increasing economical and legal importance of roughness. Different criteria can be formulated for different domains of application.

Undoubtedly, the toughest criterion for equipment approval is required for domain A. The equipment should be precise and accurate in order to be able to test the site under consideration against the roughness limits that are in force.

For domain B (acceptance of grinding work) an equipment approval procedure already exists [16]. The procedures for the other domains could be based on this procedure, at least by an extension or modification of the criteria in terms of one-third octave bands and dB re 1 μm.

Domain C requires averages of many track kilometres (rail roughness) and many train wheels (wheel roughness). Here, the noise floor need only be slightly lower than the expected average. The law of the large quantities applies: single measurements need not be extremely accurate, though systematic errors should be avoided. Indirect roughness equipment will be convenient for this type of measurements.

For applications in domain D, it is probably sufficient to refer to equipment approval procedures for one of the other domains. Otherwise, considering that monitoring of roughness growth can be required for quite different purposes, this domain may be split into subdomains.

2.5. Presentation of results

The presentation of measurement results should also correspond to the domain of application. Domains A and C, and also B in the case of acoustical grinding, require a spectral presentation similar to noise spectra.

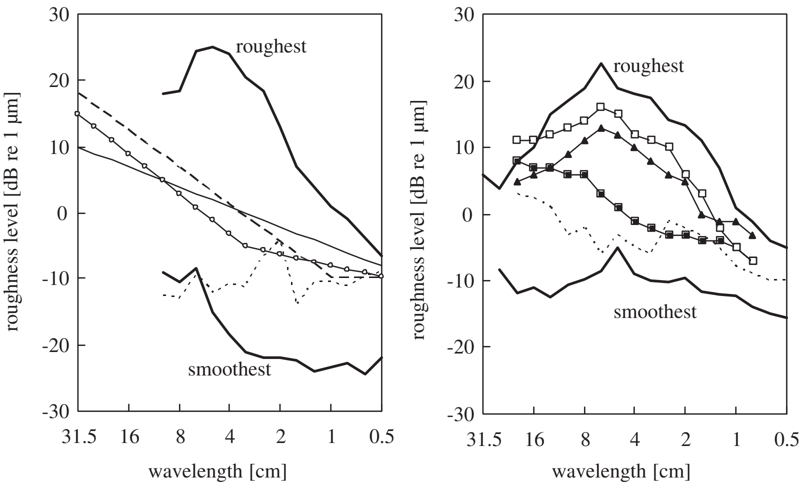

Fig. 2. Examples and range of roughness. (a) Rail roughness. Spectra for roughest, smoothest and ground rails measured by AEAT. Limit spectra for ISO3095 and TSI+ are taken from Refs. [7,25], respectively. RMR reference rail spectrum is taken from Ref. [8]. ---- Ground rails; –––– ISO3095; ○ TSI+; —— RMR. (b) Wheel roughness. Spectra for roughest, smoothest and reprofiled wheels measured by AEAT. Wheel roughness classes according to braking system have been taken from Ref. [14]. ---- Reprofiled wheels; ■ Disc brakes; ▲ Cast-iron block brakes; □ Disc brakes and additional cast-iron block brakes.

The roughness spectrum shows the dependence of the roughness level on roughness wavelength. The wavelength axis (i.e. spatial frequency axis) is reversed and labelled with octave band centres 31.5, 16, 8, 4, 2, 1 and 0.5 cm.

The roughness axis shows values per 10 dB. Roughness data are given in one-third octave bands centred at 31.5, 25, 20, …, 0.63, 0.5 cm. The aspect ratio of 10 dB:1 octave should be 4:3. Examples of such presentation are given in Fig. 2.

2.6. Benchmark test

The results of several benchmark tests in the past demonstrate the need to improve the measurement methods (including instrument hardware and analysis software).

2.6.1. Rail roughness

A benchmark test in conjunction with the Roughness Measurements workshop in Utrecht [22] attempted to separate the influence of analysis and equipment on the resulting roughness spectrum. This goal was achieved by first keeping the equipment constant and next keeping the analysis method constant. In the first case, using a single RM1200E profile, a spread of ±3 dB was found between the spectra provided by four organisations that applied their own analysis method. In the second case, using a single analysis method [23], the spectra from profiles measured by three different direct roughness instruments were compared, showing differences of less than 1 dB between the CAT (rail roughness trolley [5]) and the RM1200E (finite length rail roughness instrument [3]) for wavelengths between 25 and 2 cm. Outside this range larger deviations occurred. As the test track was rather rough, the meaning of these results for site approval measurements (ISO3095 and TSI) is only limited.

Another benchmark test was set up in the NOEMIE project [24]. Again, RM1200E profiles were sent out to a small number of organisations for spectral analysis. The differences found here were quite similar to the Utrecht benchmark, except for one profile with a large spike. As mentioned before, NOEMIE concluded that three of the presented methods were equivalent [12].

2.6.2. Wheel roughness

During the European project METARAIL (1998), the measurement results from two different direct wheel roughness instruments (an RMR1435 and a TNO made device) were compared. The comparison, which was restricted to four wheels of one freight vehicle (Rkqss), was outside the scope of the project and therefore the results were not published. Spectral differences of less than 5 dB occurred for wavelengths between 20 and 2 cm. It was estimated that the effect of these differences on the (predicted) A-weighted rolling noise level on a smooth track (with ISO3095 roughness) would be between 1 and 3 dB.

Even two instruments of the same type can produce results that differ significantly. This was noticed during a comparison of two RMR1435 wheel roughness instruments in the Dutch STV project in July 1999. The wheelsets, that were rather new, showed spiky profiles that caused differences between the instruments of up to 4 dB in some one-third octave bands. However, it is not certain that these differences can be attributed to the instruments themselves. The number and shape of the spikes have a large influence on the calculated roughness levels [24]. Small differences in lateral trace position can therefore also be an important cause of the observed deviations.

2.7. *Conclusion*

It is concluded that current equipment, as well as measurement and analysis methods, yield results that are less reliable than the rolling noise levels which they tend to be compared with. If roughness limits gain the same (legal and thus economical) importance as noise limits, the choice of equipment and analysis procedure can be crucial. This undesirable situation can only be tackled by stringent instrument specifications and validated and standardised analysis procedures, taking account of the domain of application.

3. Measurement results

3.1. *Rail roughness*

Rail roughness varies along the railway network. If the network is regularly ground, the roughness level as well as the variation of the level along the track is low. Otherwise, roughness variations up to 40 dB occur in some one-third octave bands, see Fig. 2(a). Such rail roughness variations may lead to variations in A-weighted noise level of up to 15 dB, see for example Ref. [14].

The roughest and smoothest cases in this graph are from different lines of the Dutch network, both on ballasted track with wooden sleepers. Also, the operational data is similar: both lines carried more than 80 passenger and freight trains a day at normal and constant speeds. It is then interesting to notice that the smoothest track had not been ground since it was renewed (18 years before the measurement). The RMS amplitude at the roughest site is about 40 μm.

Ground rails typically show roughness spectra around −10 dB re 1 μm. Even after a few weeks (or a million tonnes of axle load), grinding grooves are visible as peaks in the spectrum, depending on the grinding technique applied.

Also shown in the graph are limit spectra (ISO3095 and TSI +) and a reference spectrum from the RMR interim model for railway noise computations. This Dutch reference spectrum is based on roughness measurements at 30 sites reported in Ref. [14] and is supposed to represent the typical or average Dutch network rail roughness level.

3.2. *Wheel roughness*

Wheel roughness varies between trains and vehicles, but will generally depend on the braking system of the train. Disc, drum or magnetic brakes will not affect the wheel profile directly. Such wheels have generally moderate roughness. Block brakes will either smoothen or roughen the wheel tread, depending on the block material used. For example, sinter blocks tend to scour the wheel tread, leaving a rather smooth surface. Cast-iron blocks are known to generate a pattern of hard spots on the wheel tread, typically spaced 60 mm apart. In the Netherlands it is observed that the highest roughness exists on trains that have disc brakes with additional cast-iron block brakes.

Three average wheel roughness spectra are displayed in Fig. 2(b): “cast-iron”, “disc” and “disc + additional cast-iron”. These spectra are taken from Ref. [14], and are also used as references in the RMR interim model for railway noise computations.

4. Managing rail roughness

4.1. Roughness generation and growth

The roughness of wheels can be related fairly well to the (tread) braking system, but the large variation of rail roughness is much less understood. Mechanisms for rail roughness generation and growth have been studied thoroughly. A recent literature study on roughness growth was carried out by Wollstrom [26]. It is concluded therein that the factors contributing to corrugation (as a severe and visible type of roughness) are well known, but mechanisms that generate (wide-band) roughness are less investigated.

Various classes of rail roughness have been described, each with its own damage mechanism and wavelength-fixing mechanism [27]. Mathematical models have been developed, e.g. Refs. [28,29]. As the wear resistance of the rail surface layer may be the main parameter to predict the roughness growth well [30], precise knowledge of the rail material properties becomes important. Controlling these properties would then be one solution to achieve lasting smoother tracks. Other solutions relate to the design of the track and its components: reducing pad stiffness, adding rail damping, continuously supported rails. At present, however, removal of the top layer (rail grinding) is the most often practised method to treat rough or corrugated rails.

When tracks are not ground regularly, the roughness level tends to increase. It has been attempted to express the yearly increase of roughness in terms of increase of noise [31], resulting in growth rates between −1 and 9 dB per year, although most of the cases considered are between 1 and 2 dB per year. This range is similar to what is reported elsewhere [15,30].

4.2. Acoustical grinding

Removal of the corrugation layer of the rail head can be achieved by different surface treatment techniques, such as milling and grinding. An interesting development is acoustical grinding. Acoustical grinding should not be regarded as a technique by itself, but merely a purpose for which the grinding work is commissioned, namely to render tracks with a guaranteed maximum of rolling noise emission.

The acoustical grinding techniques focus on short pitch corrugation (30–60 mm) within (densely) populated areas. Various techniques are considered: with lower operational speed, with longitudinal instead of rotational grinding motion, with a polishing finish.

Acoustical grinding does not necessarily mean that the tracks are smoother or quieter afterwards than with conventional grinding, i.e. grinding for maintenance purposes. A recent study on acoustical grinding in the Netherlands [32] has reported similar noise reduction levels as known from conventional grinding [33], namely 2–3 dB(A) for rolling stock with disc brakes. The real value of “acoustical grinding” is that it ensures regular maintenance based on monitoring roughness levels and thus allows a certain noise bonus to be used in the national computation scheme. For example in Germany, the specially monitored track *BüG* [34] allows for a fixed rolling noise reduction of 3 dB(A) in the German computation model *Schall 03*.

In cases where safety regulations are becoming more stringent (UK, Netherlands) and the track possessions required for grinding work are becoming more difficult to arrange, the so-called high-speed grinding may be an alternative. Grinding is usually done at speeds close to walking speed, which reduces track availability considerably. If the speed of the grinding train is 80 km/h or higher, the track can stay in normal service and grinding trains can run between other trains. Of course, the amount of material removed at high speed in just one pass is less than at low speeds in multiple passes. This may be compensated by lowering the threshold for intervention and reducing the time interval between successive treatments.

4.3. Grinding regimes

Apart from the grinding work itself, roughness monitoring is an essential part of the grinding regime. Monitoring for the purpose of rail grinding is usually done by measurement coaches. The measurement systems are based on axle-box accelerometers [17], microphones [19] or lasers. Track sections where a certain threshold is exceeded are selected for grinding. Depending on the quality of the monitoring data, these selected

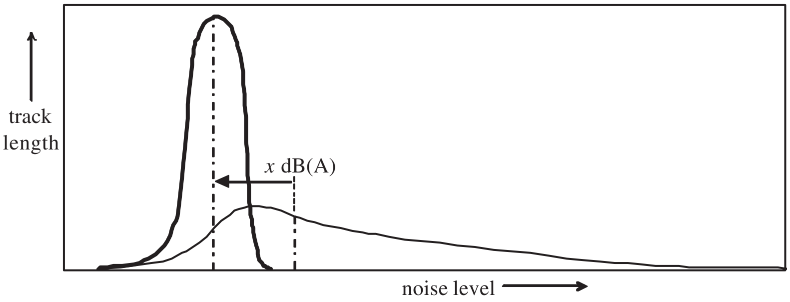

Fig. 3. Effect of a tough grinding regime on rolling noise distribution (for trains with reasonable smooth wheel treads). The distribution function is defined as the number of kilometres with a certain noise emission level. The average noise level reduces by x dB(A), but maybe even more important is that the large spread of noise levels along the track is reduced considerably. ▬ Regularly ground; — Never ground.

sections need to be inspected visually in order to assess the grinding effort (number of passes, speed and pressure) and to include the sections in the planning of the grinding programme.

A recent survey [35] shows that DB is the only infrastructure manager that applies an acoustical grinding regime, but many national infrastructure managers are considering it. From the German railway network of 60,000 km length, only 1% is controlled by the *BüG* regime. The *BüG* tracks are monitored by a measuring coach with microphone [18]. The coach is unbraked as the wheel treads need to remain smooth and free of flats. On average, only 90 km is ground annually under this regime. Monitoring is done every 6–12 months and the grinding interval time is 6–18 months.

The effect of an acoustical grinding regime is not solely the reduction of the average noise level, but also a reduction in the variation of noise levels along the track, see Fig. 3. For tracks that are never ground, a non-Gaussian distribution is found for the number of track kilometres as a function of the noise level [17,19]. The number of track kilometres with a high noise level is much larger than the number of track kilometres with a low noise level. When a grinding regime is introduced where rough sections are identified and ground, the distribution will necessarily tighten. This side effect of grinding is particularly interesting for application in noise prediction schemes (see Section 1.2.3), as the accuracy of the calculations will improve considerably. In this way, the value of noise calculations as well as noise regulations increases for the residents that live close to the track. Acoustical grinding can then be regarded as a genuine noise reduction measure.

5. Conclusions

Accurate knowledge of the rail and wheel roughness of the network will become more important for noise policy in the near future. Roughness is introduced in the latest noise prediction schemes, and most European infrastructure managers recognise that the noise emission level will become a criterion for grinding work.

Because of these developments, there is a need for improvement and standardisation of roughness measurement procedures, including specifications for approval of the measurement equipment. At least four domains of application of roughness data are to be considered, each with its own requirements for the measurement accuracy and the presented roughness quantity:

A. Roughness as part of test conditions (ISO 3095, TSI)
B. Acceptance of grinding work (ISO 13231-3)
C. Roughness as input in noise computation schemes (Harmonoise)
D. Monitoring of roughness growth (selection of grinding sections)

It is observed that acoustical grinding, at present only operational in Germany, is a potential noise reduction measure in regard of the Environmental Noise Directive of the EC. Its strength is not only the reduction of the average noise emission by a few decibels, but also the drastic reduction of the large variation of noise emission along the track (due to rail roughness variations). This will decrease the gap between measured and calculated noise emission.

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