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AEA Technology Rail BV
PO Box 8125
3503 RC Utrecht
The Netherlands
telephone +31 30 3005 144
telefax + 31 30 3005 150
email edwin.verheijen@nl.aeat.com

Harmonised **A**ccurate and **R**eliable **M**ethods for the EU Directive on the Assessment and Management **O**f Environmental **Noise**

DEFINITION OF TRACK INFLUENCE: ROUGHNESS IN ROLLING NOISE

***Deliverable 12 part 1* of the HARMONOISE project**

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Annemarie van Beek and Edwin Verheijen			

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Name	Date	Signature
E. Verheijen, AEA WP7 leader		
H. Jonasson SP, WP1.1 leader		
C. Talotte SNCF, WP1.2 leader		
F. De Roo, TNO, WP2 leader		
H. Van Leeuwen, DGMR, WP3 leader		
D. Kühner, DeBakom, WP4 leader		
D. Van Maercke, CSTB, WP5 leader		

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Summary

Rolling noise is the noise from vehicle and the track that occurs when a wheel runs on the track. Irregularities on the surfaces of wheel and track, referred to as roughness, cause vibrations that lead to the generation of noise. It appears that the variation in noise emission level, due to variations in the rail roughness across the network, can be as large as 20 dB(A).

In existing calculation schemes, however, rail roughness is not taken into account as a separate parameter. To achieve an accuracy of noise calculation that approaches the objectives of the HARMONOISE project, roughness can no longer be ignored.

Previous research on the roughness issue has resulted in several measurement and analysis methods that characterise roughness in terms of a roughness (excitation) spectrum. Though a review of these methods shows that there is a need for further standardisation, the accuracy of the resulting roughness spectra of the current methods is such that a linear relationship between the roughness spectrum and the noise emission spectrum can be assumed. This linearity means that the roughness spectrum can directly be used to calculate the source power spectrum of the railway noise sources.

For wheel roughness, a dependency between the type of braking system and the wheel roughness level is observed. Generally speaking, cast-iron brake blocks generate high wheel roughness and other braking systems do not. A classification can therefore be efficiently based on the braking system of the trains on a network. A typical wheel roughness spectrum is assigned to all trains of a particular braking system.

A classification system for rail roughness can probably not be based on external track features, as available statistical data reveals no obvious correlation between rail roughness and such features. It is shown, however, that the spread depends largely on the maintenance regime of the track or network. Specially monitored track (controlled by regular monitoring and grinding) reduces rail roughness where necessary, thereby reducing the spread considerably.
This classification problem leaves two basic options for rail roughness in prediction models:

(a) Using an *average* rail roughness spectrum for the network. The consequence of this approach is that the calculated noise may deviate much (~10 dB) from the actual noise at smooth or corrugated track sections.
(b) Using *measured* roughness per section of track, by monitoring roughness regularly. This reduces the deviations in the prediction model to approximately ±1 dB. The consequence is that, apart from monitoring, also the database with source data and hence the calculations are to be updated regularly.

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1 Introduction

Rolling noise is the noise from vehicle and the track that occurs when a wheel runs on the track. Irregularities on the surfaces of wheel and track cause vibrations that lead to the generation of noise. It has been proved that the level of roughness is proportional to the generated noise levels. In existing calculation schemes, roughness is not taken into account as a separate parameter. The effect of wheel roughness is implicitly taken into account in the different train categories. For rail roughness, an average value is implied if the underlying pass-by measurements have been taken at many track locations.

To achieve the accuracy that is desired in the HARMONOISE project, roughness can no longer be ignored. Roughness has a significant effect on the year average of L_{den}. If roughness is an explicit parameter in the calculation scheme, it will sooner be recognised that reducing roughness levels has positive effect on the noise level. In this way, roughness control as a noise measure is stimulated.

This report deals with the present day knowledge of roughness in relation to noise and a proposal for practical implementation in the HARMONOISE model.
Chapter 2 describes the measurement and analysis methods. Chapter 3 shows statistical data and proposes a classification systems for roughness.
Chapter 4 describes how roughness can be added into the calculation scheme for rolling noise and how it can be dealt with in practice.

2 Roughness measurement methods

2.1 Introduction

Rail roughness varies along the track. Roughness measurements on different sites show variations up to 40 dB in some third octave bands. A measurement campaign in the Netherlands showed that rail roughness variations lead to noise level variations of up to 15 dB(A) [9]. Wheel roughness varies between different trains (see Section3.1.1), and is responsible for noise level differences as large as 10 dB(A).

Rail and wheel roughness can be measured in a 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 separately. The most frequently used systems employ displacement transducers or accelerometers in sensors that touch the rail or wheel surface. Several types of instruments have become commercially available since 1990.

Indirect method: a measurement procedure in which the total effective roughness of rail and wheel are determined. Indirect measurements are carried out either on-board a running train (using axlebox accelerometers or bogie microphones), or at the track by measuring rail vibrations during train pass-bys.

Direct methods can distinguish between rail and wheel roughness, which make it possible to apportion responsibility for corrugated tracks or rough wheels to track owners and vehicle owners. Indirect methods do not have this advantage, unless very smooth wheels or rails with known roughness are used. On the other hand, indirect methods 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 effect.

Indirect methods have in common that they determine the combined roughness of rail and wheel. Once the roughness of the wheel and the rail is added in the contact patch, there is no means to separate their contributions (in post-processing). There are, however, special cases in which these contributions can be estimated.

Until now, the spread of practical experience with roughness measurements and analyis is limited to a few railway administrations and research institutes in Europe. Some of the methods described in this report are less established than others.

Several direct and indirect methods have been explored in the Metarail and STAIRRS projects. The following section gives an outline of methods. In addition, some measurement instruments are described briefly.

2.2 Direct methods

2.2.1 Rail roughness

The pr EN ISO 3095:2001 standard describes how rail roughness shall be measured to support interior and exterior noise type testing measurements. Although not officially accepted yet, this standard is the only widely spread protocol for rail roughness measurements that can be referenced to.

Since its first issue in 1999, experience in Metarail and STAIRRS has learned that the roughness spectrum that results from this protocol has reasonable reproducibility (within ±1 dB). Lack of knowledge about the (lateral) position of the wheel/rail contact patch and contact spring's filtering effects, however, may lead to discrepancies between the rail roughness measured and the actual rail roughness excitation experienced by the wheel/rail system. It is estimated that an accuracy better than ±3 dB[1] is impossible at present. To increase the accuracy of the method, it will be necessary to take into account several specific properties of the train and track involved. Hence, measuring more roughness samples will *not* enable a better prediction of the rail roughness excitation.

Equipment

The ISO 3095:2001 version of the standard (section D.1.2.2) gives the following prescription of the measurement instruments:

> Direct roughness measurements are performed with a standard roughness measurement instrument placed on the railhead. The instrument contains a measurement probe that is guided along the rail, measuring the relative height of the railhead in micrometers.

This prescription allows for the use of typical instruments of 1.2 m length, like RM1200E (by Müller-BBM) and TRM01 (by ØDS), but also for trolley systems like CAT (by Loram) and RMF (by Vogel and Plötscher) at walking speed. Even systems based on measuring coaches, e.g. with laser probes, are allowed as long as the reference height is sufficiently stabilised[2].

Wavelength range

The accuracy of the roughness level of the longer wavelengths, measured by typical measurement instruments of 1.2 m length, is limited due to this instrument's length. It is practice to render one-third octave band spectra not wider than 10 cm wavelength. The lacking of longer wavelengths than 10 cm, however, limits the applicability of roughness spectra for high speed trains. Before answering the question 'what range is needed?' it should be recognised that from the view-point of dynamics, it does not make sense to expand the roughness wavelength range further than the spacing of the sleepers or rail fasteners. As it can be expected that rail bending will govern excitation wavelengths of the order of sleeper spacing, the STAIRRS project proposes to extend the wavelengths to 31.5 cm, being about half the typical sleeper spacing. At 300 km/h this roughness wavelength corresponds to about 260 Hz.
Using instruments with 1.2 m of length, a wavelength up to 31.5 cm can be derived if a few sections are added near the centre of the reference section of the ISO 3095 measurement protocol [1]. For trolley-based and coach-based instruments the measurement of wavelengths up to 31.5 cm is generally no problem, but resolution or accuracy may restict their use in wavelength bands shorter than a few centimetres.

An efficient rail roughness measurement protocol

The knowledge gained in the STAIRRS project has resulted in a more efficient protocol than described in prEN ISO3095:2001. This protocol is described in Appendix 1.

2.2.2 Wheel roughness

To date, there is no standard direct wheel roughness measurement method. It is proposed to develop a default method in HARMONOISE based on knowledge from previous European projects. A wheel roughness measurement standard should link up with the rail roughness standard regarding measurement accuracy, reproducibility and equipment specifications.

Overview of protocols used in projects

- In the 1998 EuroSabot short term field test (EU project on brake block development), parallel roughness lines were taken at fixed distances, measured from the outer face of the wheels: 37.5 mm to 82.5 mm in seven steps of 7.5 mm. The instrument was an RMR1435 manufactured by Müller-BBM.

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[1] *3 dB inaccuracy in rail roughness leads to 3 dB(A) inaccuracy on corrugated tracks, but only to 1 dB(A) inaccuracy on smooth tracks.*

[2] *Axle-box vibration systems on measuring coaches **do not** measure the rail roughness independently of the coach's wheel roughness. These systems must therefore be classified as indirect methods.*

- The protocol used in the 1999 Metarail Round Robin campaign prescribed the measurement of 3 parallel lines on the wheel tread, at fixed lateral offsets, being 60, 70 and 80 mm from the inner face of the wheels (flange). The instrument was a TNO-TPD prototype.
- The protocol used in the 2001 STAIRRS validation campaign required 5 parallel lines to be measured. Here, the lines were measured with respect to the centre of the running surface, with intermediate spacings of 5 mm. The instruments were an SNCF prototype and an RMR1435.

Equipment

The instruments used in these campaigns featured either tangential or longitudinal transducers. The instruments are placed on the railhead, close to the wheelset that was jacked up slightly. The wheelset is turned by hand. The instruments measure one, three or five simultaneous parallel lines per wheel. The instrument measuring only one line was equiped with two probes, enabling to measure both wheels of one axle simultaneously.
On some instruments, the wheel profile was derived as a space-domain average of 3 revolutions. On other instruments only one revolution was taken. Then, a one-third octave band spectrum was derived from each profile line, which was averaged quadratically with the other parallel lines of one wheel. At least one axle per vehicle involved was measured this way. Both wheels of that axle were considered this way, which enabled to render a vehicle average (though based on one axle only).

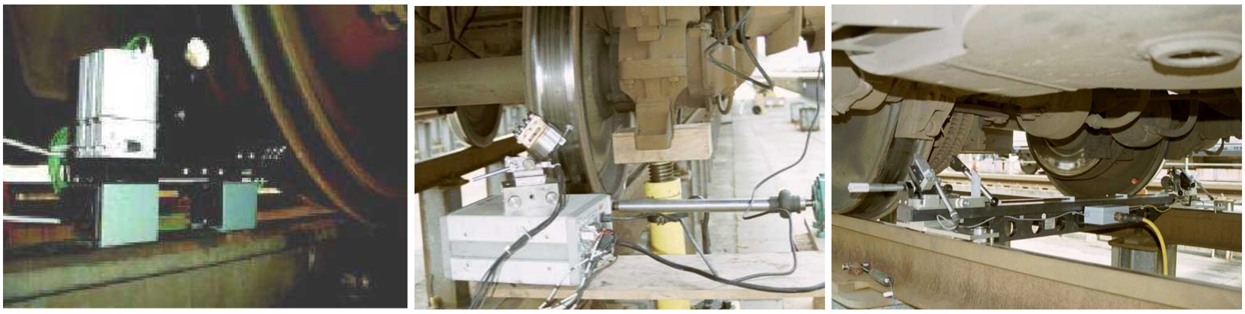


Figure 1: Various wheel roughness instruments, left to right: RRM01 (by ØDS) with 3 probes, SNCF prototype with 5 probes, RMR1435 (by Müller-BBM) with 1 probe at each wheel. The TNO-TPD instrument that was used in Metarail is not displayed.

An efficient wheel roughness measurement protocol

Appendix 2 contains a proposal for a direct wheel roughness measurement protocol, based on the above experience.

2.2.3 Direct roughness processing

The processing of measured roughness from a set of lines into a roughness spectrum is not straightforward. There is no official processing method that is agreed upon yet. However, the present day processing proposals are reasonable close, though they may reveal large differences in special cases. As long as an ISO standard for direct roughness analysis is not achieved, it is proposed to use the method described in Appendix 3.

2.3 Indirect methods

Indirect methods have in common that they determine the combined roughness of rail and wheel. Once the roughness of the wheel and the rail is added in the contact patch, there is no means to separate their contributions (in post-processing). There are, however, special cases in which the contributions can be estimated. First the methods to measure combined roughness are described, then the special cases are given.

2.3.1 Measuring combined roughness

Combined roughness, the energy sum of wheel and rail roughness, can be measured either on a vehicle by axle-box vibration or sound pressure near the wheels, or on the track by measuring vertical rail vibration. The first two methods are useful for surveying track roughness, the third is most suitable for surveying wheel roughness within individual trains.

Via axle-box vibrations

Roughness can be monitored by measuring axle-box acceleration spectra from the moving vehicle (measuring coach).

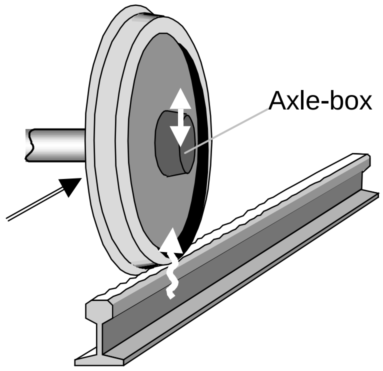


Figure 2: Axle-box vibrations.

The combined roughness excitation spectra can be derived from these vibrations, for example by adding a speed-dependent transfer function. The accuracy of this method is limited by the wheel roughness and by the modal behavior of the wheel vibrations. If the wheel roughness is known, either by measuring a smooth rail or from direct wheel roughness measurements, the rail roughness can be distracted from the combined roughness. Measuring coaches of NS, LUL and other railways apply axle-box accelerometers to obtain an overview of the network's rail roughness.

Via bogie sound pressure

By measuring the sound pressure generated in or near the bogie of a vehicle, a direct link between roughness and noise creation can be made. The German national calculation scheme uses this idea in a noise measuring coach (*Schallmesswagen*) to check if the noise level of certain tracks still is within legal limits (so-called *Besonders überwachtes Gleis* [12]). This method is also applied by SNCF to obtain an overview of the network's rail roughness. AEA Technology Rail supplies the NoiseMon system [13] that can be used under any train to monitor rail corrugation.

Via rail vibrations

A validated rail vibration method is the Indirect Roughness (IDR) method developed by TNO in Metarail [2]. In this method, vertical accelerometers are placed under the rail foot near the sleepers, see Figure 3. Using rail vibrations, the spatial rail decay function and a conversion spectrum depending on wheel diameter and axle load, it is possible to calculate the total combined roughness of a single wheel passage.
The Indirect Roughness method is incorporated in the revised Dutch measurement prescription of the calculation scheme [15].

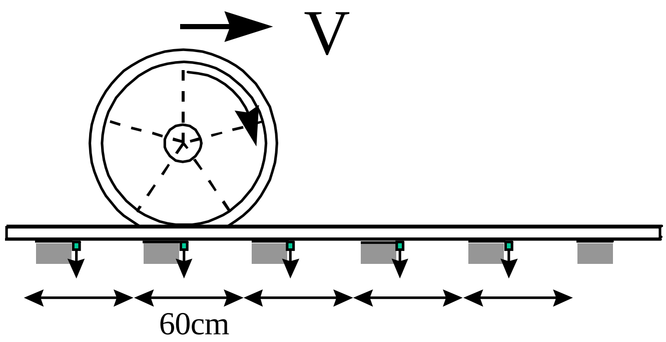


Figure 3: Indirect roughness method (taken from [2]).

2.3.2 Rail roughness

If the wheel roughness of the vehicle-based methods (axle-box and bogie sound pressure) is sufficiently low, these methods can be used to monitor the network's rail roughness.

The IDR method can be used in 2 ways to determine the rail roughness:

- By plotting a spectral graph of a large number of single wheel passages (i.e. many trains) on one site, the lowest occurring value per one-third octave band is an upper bound of the rail roughness on that site.
- In case of known wheel roughness, preferably of smooth wheels, the rail roughness can be calculated by subtraction.

2.3.3 Wheel roughness

The wheel roughness of the measurement wheel or bogie of the vehicle-based methods can be estimated from a graph with many *combined* roughness spectra. The lowest occurring value per one-third octave band will be an upper bound of the wheel roughness.
If the rail roughness is known at a site where IDR-equipment is installed (for instance using the wheel roughness upper bound estimation), the wheel roughness can be derived by subtraction. If installed on a very smooth track, the wheel roughness will equal the combined roughness.

2.4 Roughness presentation

To facilitate easy understanding of roughness spectra and to enable comparison between results, it is necessary to standardise the grahphical presentation of results. Appendix 4 describes a way of presentation that is close to the standard for presenting noise spectra.

It is possible to produce a single value indicator for roughness. Several indicators have been proposed in the past, non widely accepted. Reference [18] describes a quantity called $L_{\lambda CA}$ (unit [dB]) which is more or less proportional to the pass-by noise level. Appendix 7 gives the calculations involved and provides typical values for rail and wheel roughness. The accuracy of such indicators with respect to noise is limited by definition, as the spectral shape of the noise spectrum depends on other train and track characteristics than only roughness. However, the effect of spectral changes in roughness (e.g. the effect of rail grinding) on the noise level can be assessed within ±1 dB(A).

2.5 Contact filter

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

$$R_{eff} = R_{dir,rail} \oplus R_{dir,wheel} + CF$$

In words: the indirectly measured total roughness, alternatively called the combined effective roughness, equals the energy wise summation of directly measured rail and wheel roughness, to which a contact filter has been applied. Appendix 5 shows the dependence of the contact filter on wheel radius and axle load.
It must be remarked here that discrepancies as large as 3 dB in certain one-third octave band occurred during the checking of the above rule in the STAIRRS project. Here, indirect and direct measurements were compared. Further research is required in order to better specify the indirect and direct measurement and analysis methods.

3 Roughness levels and classification

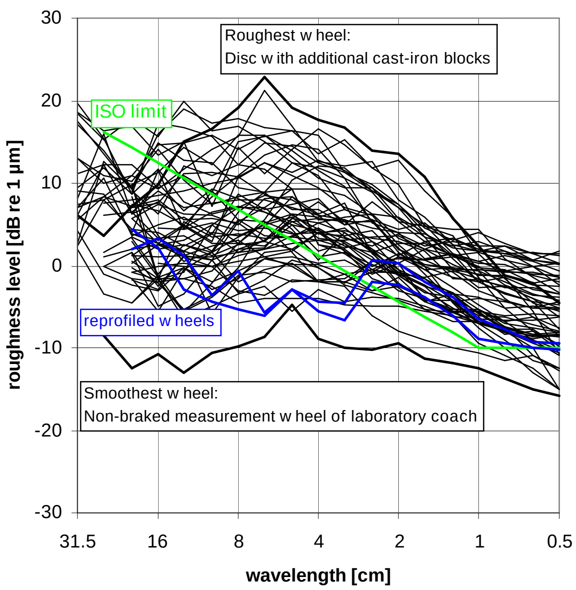
In this chapter, current knowledge of the variation of roughness levels is considered, with the aim to find a basis for classification for a calculation scheme. Sections 3.1 and 3.2 deal with wheel and rail roughness respectively.

3.1 Wheel roughness

Wheel roughness varies between trains and vehicles, but will generally depend on the distance run after wheel reprofilation and on the braking system used. Newly reprofiled wheels reveal a pattern of rings due to the carvings of the chisel. After a few hundreds or thousands of kilometres of train operation this pattern vanishes.

3.1.1 Variation depending on braking system

The typical roughness profile on the wheel tread depends on the braking system. 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. On the one hand, sinter blocks tend to scour the wheel tread, leaving a rather smooth surface. On the other hand, cast-iron blocks are known to generate a pattern of hard spots on the wheel tread, typically spaced 6 cm apart. In the Netherlands it has been observed that the highest roughness exists on trains that have cast-iron blocks in addition to disc brakes. Generally speaking, freight vehicles with cast-iron blocks also have high roughness.
Figure 4a shows spread, minimum and maximum of wheel roughness spectra. The measurements were carried out with the TNO-TPD prototype system and with an RMR1435 (see section 2.2.2). A large number of Dutch and French passenger and freight wheels were measured. The smoothest wheel is a non-braked laboratory coach wheel. Freshly reprofiled wheels are 5 to 10 dB rougher.



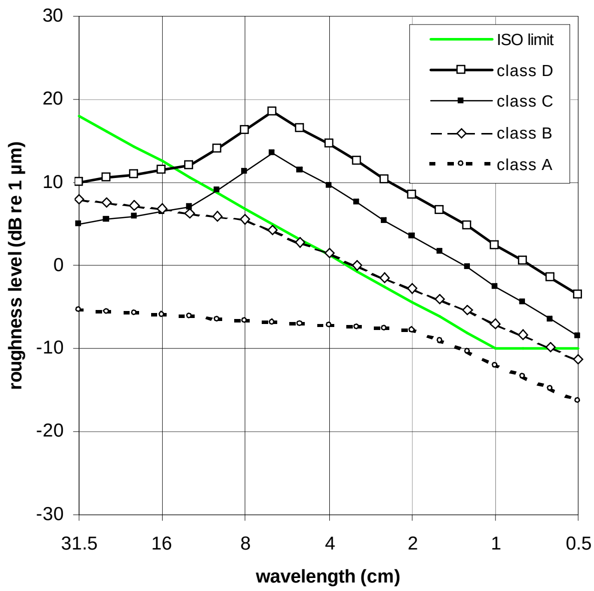


Figure 4a: Examples and range of wheel roughness. **b. Classification example based on braking system.**

3.1.2 Dependence of wheel roughness on mileage

For cast-iron braked wheels, it has been observed in the Netherlands [17] that, after reprofiling the wheels, the reprofilation grooves vanish within 1000 km and then wheel roughness growth

rapidly until 10000 km of mileage. After this period, the wheel roughness tends to stabilise. Figure 5 shows the effect of mileage for 4 types of braking systems of Dutch rolling stock. For mileages below 10000 km, only data for cast-iron trains is available.
In a recent German study [16], it is found that the wheel roughness of ICE3 (high speed trains with disc brakes) does not significantly depend on the mileage, see Figure 6.
These results suggest that, once the wheels have run in, mileage is not important any more for the noise level.

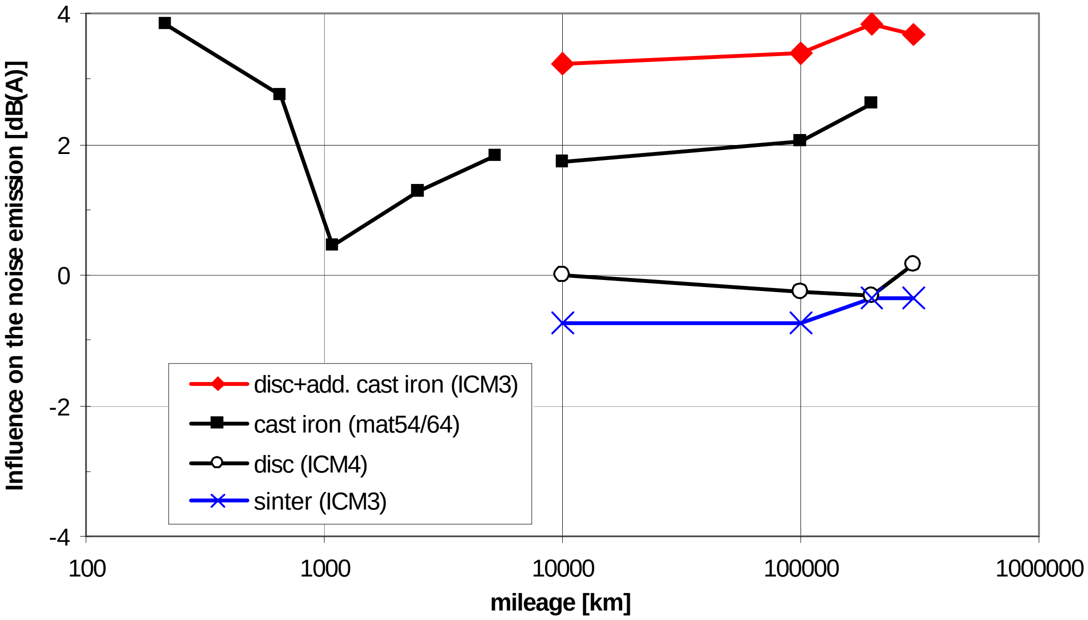


Figure 5: Effect of wheel roughness growth on the noise emission. The noise level is calculated using spectra of measured wheel roughness and average Dutch rail roughness. The level at 10000 km for disc is the reference level.

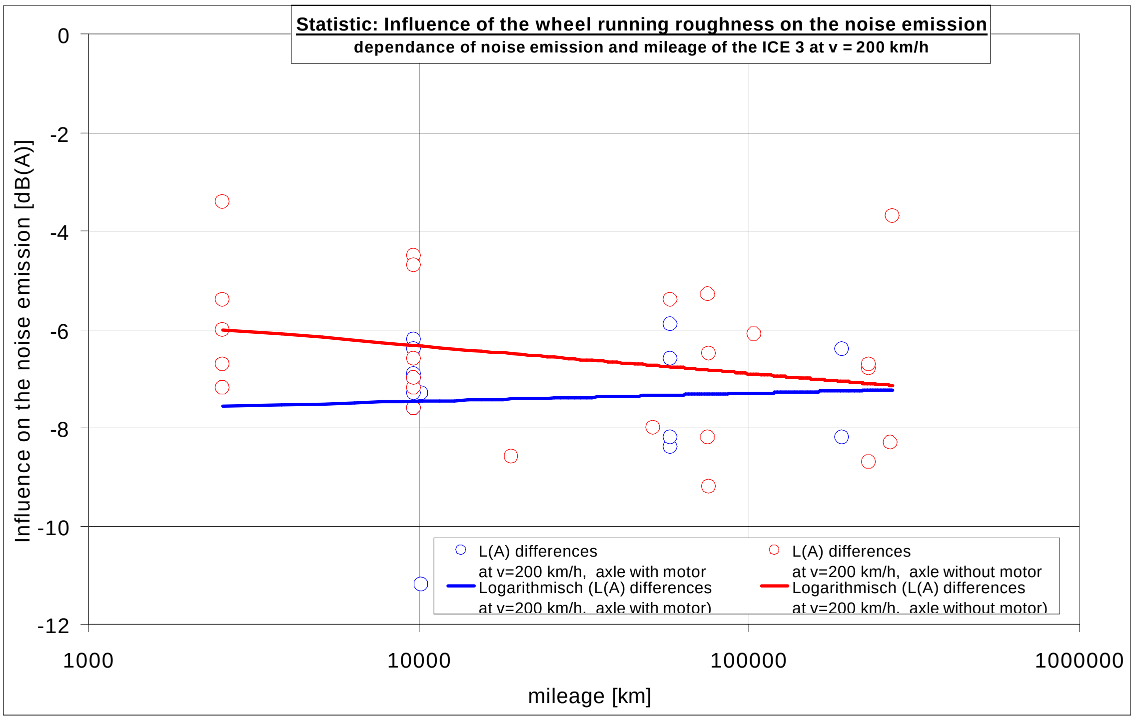


Figure 6: Dependance of the noise emission and the mileage of ICE 3 wheelsets for the velocity 200 km/h. The reference wheel-rough-ness was 0 dB for the frequency range 50 Hz to 8 kHz. The ICE 3 has driven axles with motor (blue) and also non driven axles (red). Given are values calculated with (1) and the trend lines. Figure taken from [16].

3.1.3 Classification example

As it is recognized that wheel roughness varies with braking system, a classification system for wheel roughness can be based on the designated type of braking system of a vehicle. Figure 4b shows an example of how a set of wheel roughness classes could look like. shows a set of styled curves. The roughest and smoothest are based on the minimum and maximum curves in Figure 4a. Curve D is equal to curve C + 5 dB. Curve C for cast-iron block-braked and curve B for disc-braked wheel are derived from [6].

Vehicles and trains can then be classified in the following way:

- Trains with cast-iron blocks in addition to disc brakes are class D.
- Trains with cast-iron blocks are class C.
- Trains which are non-tread braked are class B.
- (Future) trains under special regime that keep the wheels smooth are class A.

Trains with braking types that are not mentioned here must be classified after measuring a representative population (e.g. composite brake blocks).

Table 1: Typical roughness spectra [db re 1µm] for wheel roughness classes.

wavelength [cm]	31.5	25	20	16	12.5	10	8	6.3	5	4	3.2	2.5	2	1.6	1.3	1	0.8	0.63	0.5
class D [dB]	10.0	10.5	11.0	11.5	12.0	14.1	16.2	18.5	16.5	14.5	12.6	10.5	8.5	6.6	4.8	2.5	0.6	-1.5	-3.5
class C [dB]	5.0	5.5	6.0	6.5	7.0	9.1	11.2	13.5	11.5	9.5	7.6	5.5	3.5	1.6	-0.2	-2.5	-4.4	-6.5	-8.5
class B [dB]	8.0	7.6	7.2	6.8	6.4	6.0	5.6	4.2	2.8	1.4	0.1	-1.4	-2.8	-4.1	-5.4	-7.0	-8.4	-9.8	-11.2
class A [dB]	-5.4	-5.6	-5.8	-6.0	-6.2	-6.4	-6.6	-6.8	-7.0	-7.2	-7.4	-7.6	-7.8	-9.1	-10.4	-12.0	-13.4	-14.8	-16.2

It must be remarked that the data on which the above classification example is based, is gathered in different countries, using different measurement and analysis methods. No proof is given here whether the wheel roughness of a Dutch disc-braked train is the comparable to that of an Italian disc-braked train. More measurement data, using a standardised protocol, is required for any official classification system.

3.2 Rail roughness

3.2.1 Rail roughness levels

The spread of rail roughness between various tracks is quite large. Figure 7 gives an idea of the spread of rail roughness in the Netherlands. This figure shows the following data, resulting from direct rail roughness measurements:

- site averages of 30 arbitrarily chosen sites in the Netherlands
- a heavily corrugated track
- ground tracks, a couple of weeks after grinding.

Rails are usually smoother than wheels: the smoothest rail is smoother than the smoothest wheel. Also, notice that the spread of rail roughness is larger than of wheel roughness. It can also be seen that ground tracks have a rail roughness that is comparable with the lowest in the range of the 30 (non-ground) sites.

Rail grinding produces a variety of roughness spectra. At present, grinding techniques are being adopted to requirements of low rolling noise. One of the issues to tackle is the difference in vocabulary between grinders ('wave depth', 'short waves') and acousticians ('roughness spectrum' and 'one-third octave bands').

Unlike classification of wheel roughness, rails cannot (yet) be classified based on track construction or track operation features. There is not much evidence for the claims that rail corrugation is less probable to develop on continuously supported tracks and that high speed lines are smoother than other tracks. Also, the claim that lines with much freight show more corrugation than passenger lines did not stand in the Netherlands [9].

It must therefore be concluded that, in absence of reliable and representative data, there is no proved dependence between the rail roughness condition and the track construction or track operation. Because of that, a rail roughness classification system, if possible at all, must be based on measurement results, not on assumptions.

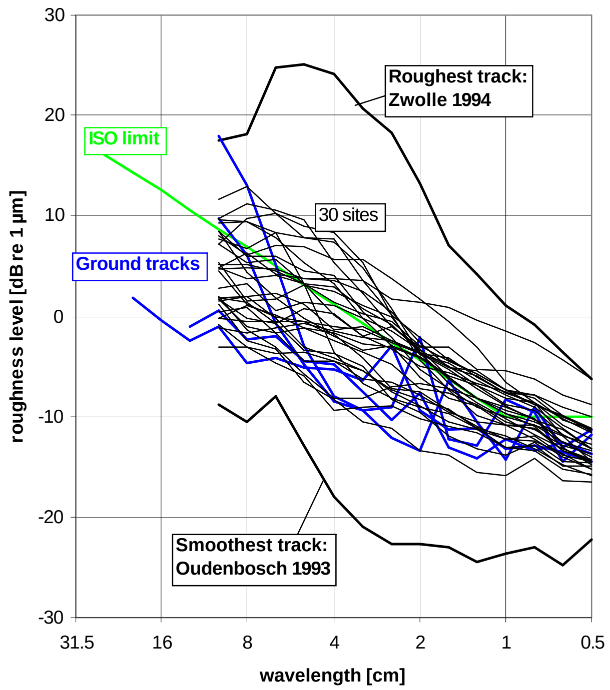


Figure 7: Examples and range of rail roughness.

3.2.2 Rail roughness statistics

Insight in the spread and distribution of rail roughness has been obtained in an extensive study in the Netherlands in 1999 [9, 10]. About 4200 km track has been measured by means of an axle-box vibrations measurement system, called MSAR. The output of this system is a one-third octave band spectrum from 20 cm to 0.4 cm. A median filter was used on these spectra to neutralise the influence of joints, bridges, switches, flange contact on the axle-box vibrations. For every segment of 100 meter, an average spectrum has been calculated.

One of the statistic exercises was to find the Dutch average rail roughness spectrum. Apart from the overall average also an average was considered that leaves out the corrugated pieces of track. Corrugated rail was separated using the following definition for corrugation: if the roughness spectrum shows a roughness level of 15 dB or more in the 4 cm octave band. Such cases correspond more or less with visual detection of corrugation. Based on this criterion, it was found that about 10% of the network is corrugated.
Figure 8 shows that the spectrum of corrugated track is much higher than the roughness of the not corrugated track. Because the limited occurrence of corrugation, the influence on the average network roughness is very small.

A second exercise in statistics was to determine the roughness distribution across the network. This would answer the questions "how many kilometres of track have a certain roughness level?" and "is the roughness distributed according to a gaussian (normal) distribution?".

Using the roughness data on the network, the noise level at 7.5 m from a disc-braked train (speed 140 km/h) was calculated. The average value is 88 dB(A). Figure 9 shows this distribution for the whole network, for the corrugated part of the network and for the non-corrugated part of the network.

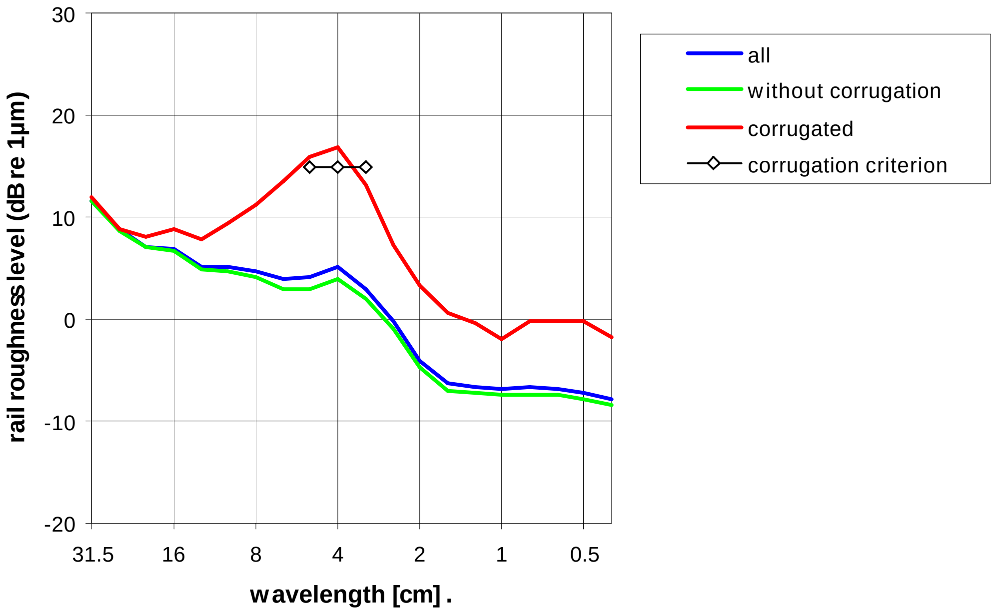


Figure 8: Average rail roughness spectra in the Netherlands in 1999.

This distribution reveals a non-gaussian shape for the noise creation level as calculated for a disc-braked train. The lowest level lies 2 dB(A) below the average, while to highest level is about 17 dB(A) above the average. Note that even if the rail roughness itself would be distributed in a gaussian sense, the wheel roughness of that train would cause a threshold of noise creation. On the other hand, note that using the axle-box vibration method, the lowest rail roughness level measured depends on the wheel roughness of the measuring coach. It is estimated that the lower boundary is overestimated by about 2 dB(A) due to this effect. Using this estimation, the minumum and maximum in the distribution lie 4 dB(A) below, and 17 dB(A) above the (weighted) average of 88 dB(A).

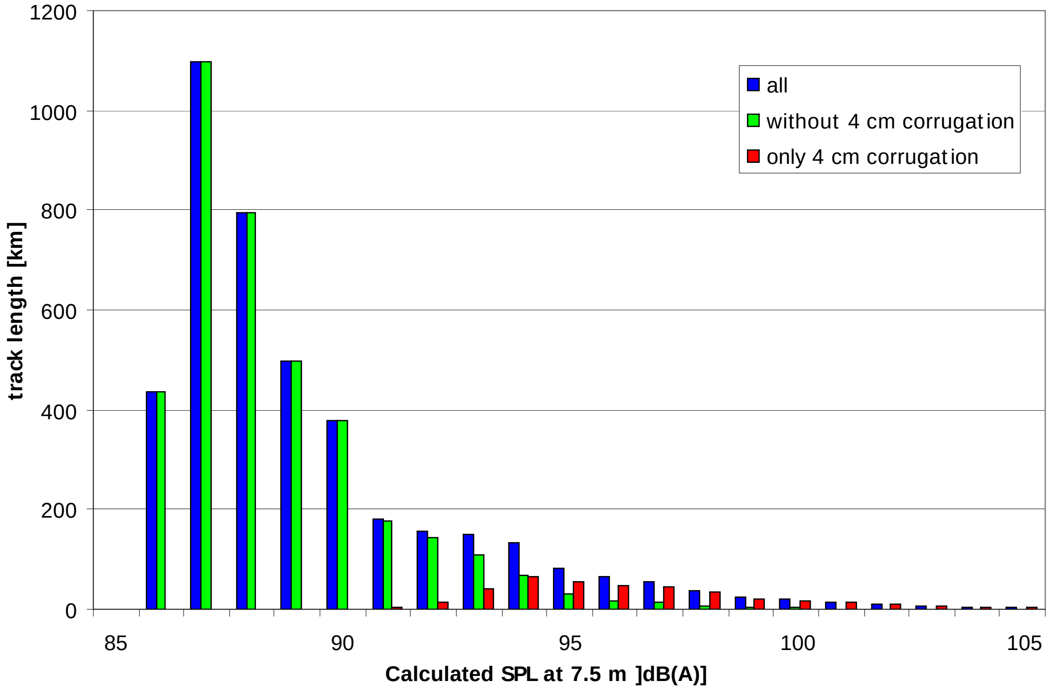


Figure 9: Distribution of roughness, shown as its influence on the noise level of a disc-braked train.

Effect of grinding regime

An important parameter that determines the shape of the distribution is the grinding regime. In the Dutch case in 1999, no so-called acoustical grinding was applied. Only tracks segments with severe corrugation of approximately 100 µm wave depth (short waves up to 0.3 m) were selected for grinding, while it must be mentioned that there was a backlog of grinding such selected tracks.

The German specially monitored track (*BüG* [12]) constitutes a grinding regime that lowers the average noise creation by 3 dB(A) for disc-braked rolling stock. Such regimes must therefore show a distribution that is truncated at the high end, see Figure 10.

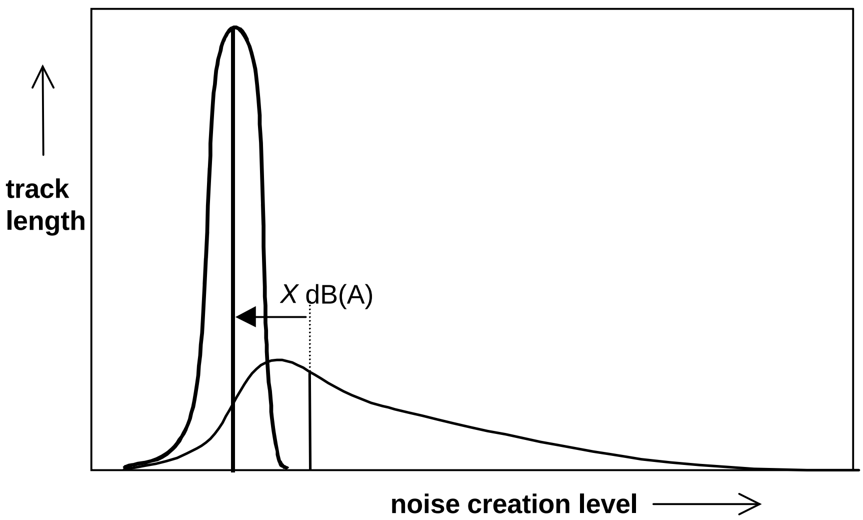


Figure 10: Effect of a tough grinding regime on rolling noise distribution.

3.2.3 Accuracy of basic calculation methods

Now the spread of rail roughness has been discussed, the desired and achievable accuracy of rail roughness measurement, calculation and classification can be treated.
This is done for the following cases:
(a). *Using one imposed or estimated roughness spectrum for the network*. This case can be thought of as using one class of roughness. The average roughness spectrum can be determined from measuring roughness at a sufficiently large sample of the network.
(b) *Using (periodically) measured rail roughness*. In this case every segment of the network (e.g. 100 m) has a unique rail roughness spectrum. As this spectrum varies in time, it should be measured periodically. Probably using a measuring coach is the only efficient option. However, it is not likely that this method renders a practical and useful calculation scheme. Therefore, a simplification may be considered by introducing rail roughness classes. The network will still be monitored regularly. The roughness spectrum of every section of the network is then rounded to the nearest roughness class. The calculation scheme uses the class average roughness for noise creation calculations.

The accuracy of the noise creation levels calculated according to the above cases is now assessed.

In case (a), the accuracy depends directly on the spread in rail roughness. This spread will generally depend on the maintenance regime and will therefore vary between countries (or smaller administrative regions). Though rail roughness can vary in a range of 40 dB (see Figure 7), the range of noise creation is limited to some 20 dB(A) due to wheel roughness [9, 10]. Note that this distribution is non-gaussian. This means that, once a reliable and representative average rail roughness spectrum has been assumed, the actual noise emission on a certain site can be about 4 dB lower, but also as much as 17 dB higher than the average (calculated) noise emission. By applying a special grinding regime, the distribution can be truncated so as to lower the average roughness and to reduce the spread. In case of the German *BüG*, the average is shifted 3 dB(A) downward. The spread must reduce considerably, see Figure 9. An error of less than ±2 dB(A) can probably be achieved using a tough grinding regime.

In case (b) the accuracy of the emission calculations depends on the monitoring accuracy. Using the axle-box measuring coach equipped with MSAR (see previous section), an error of less than ±2 dB can be achieved. This is demonstrated in Figure 11, which compares direct measurement (with RM1200E) and indirect measurement (with MSAR) at three test sites. Because of smearing out in time (annual variance) and space (variance along track), the effect of the measurement error on noise creation will probably reduce to ±1 dB.
If a classification system is used after the collection of the monitoring data, the accuracy depends on the range of the classes. In Appendix 6, the classification system described in the Danish draft version of the ISO 3095 standard [7] is used as an example to calculate the accuracy. It is shown that the *noise level* of consecutive *rail roughness classes* differs less than ±2 dB(A), reducing the error to less than ±1 dB. Taking account of the above measurement error, the overall error will probably lie between 1 and 2 dB.

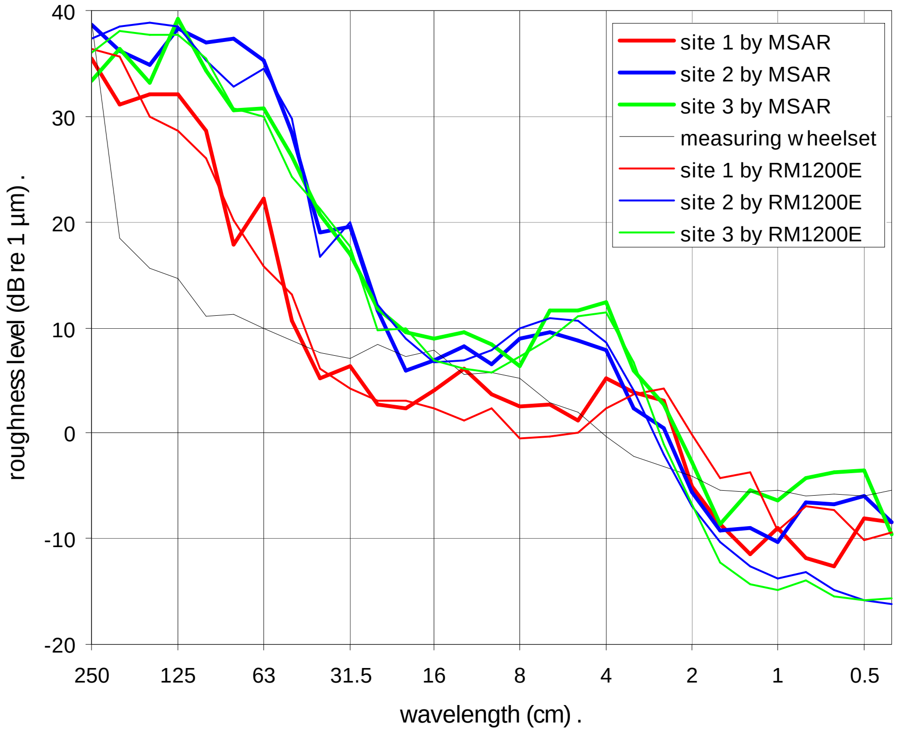


Figure 11: Comparison of axle-box vibration spectra (MSAR) with direct measured spectra (RM1200E and RMR) shows that the measurement method can achieve a very good accuracy for wavelengths between 2 and 250 cm.

4 Conclusions and recommendations

This chapter concludes on the findings of the previous chapters, and proposes practical methods to incorporate wheel and rail roughness in a prediction model. At this point, it is important to keep in mind the desired output of the calculation scheme: the yearly averaged noise level L_{den}.

4.1 Wheel roughness

The actual noise level of a train pass-by is influenced by the actual roughness of the wheels of that train. Because the calculation scheme produces an average noise creation value, knowing the average representative wheel roughness of a certain train category is sufficiently accurate in order to determine the (average) L_{den}.
The wheel roughness of trains in operational service cannot be easily or efficiently measured with a direct roughness method. Two determination schemes are possible, one using typical wheel roughness, and the second using indirectly measured wheel roughness.

4.1.1 Typical wheel roughness

In case of determination of typical operational wheel roughness for a certain train class, it is proposed to measure three different trains belonging to that class, with a mileage between 10,000 km and 100,000 km (see Section 3.1.2). Trains are measured in compliance with the wheel roughness measurement protocol (Appendix 2). The typical roughness spectrum for that class is the average (in the energy sense) of the measured spectra per train. The typical roughness should be determined every 5 years, or earlier if the braking type or maintenance programme is changed significantly.

4.1.2 Indirectly monitored wheel roughness (recommended)

The wheel roughness of operational trains can be determined by measuring indirect roughness at a measurement site with known (directly measured) low rail roughness. This method is recommended. Though its measurement accuracy is maybe lower than with direct measurement, the large number of trains enables the determination of a more representative wheel roughness spectrum.

4.2 Rail roughness

For rail roughness, it has been shown that the spread in roughness levels is large, and that classification cannot be based on track type (like braking type for wheel roughness). Knowing *how large* the spread of roughness is across the network, can help to decide how roughness is incorporated in the prediction models.
There are basically two ways to cope with rail roughness:
(a) To assign an average spectrum to a track or network.
(b) To monitor rail roughness regularly and to update the database of the prediction model accordingly, with a *measured* rail roughness spectrum for each track section.
The accuracy of the prediction model in approach (a) may be poor. It is shown that the deviation between actual noise and predicted noise may be as large as 17 dB for a corrugated track.
In special cases, e.g. by applying a tough grinding regime, the spread of roughness across the network can be reduced considerably.
In approach (b), the noise emission level can be calculated within ±1 dB accuracy. However, it requires much more effort in measuring, updating the source database, and updating calculations. This approach has been studied by NS Railinfrabeheer between 1997 and 2001 (see e.g. publication [10]), but has not (yet) resulted in a dedicated monitoring and calculation procedure.

Using a rail roughness classification system in addition to approach (b), will only slightly deteriorate the accuracy. The advantage of classification for prediction models, though, is limited as it only reduces the size of the source database. Monitoring is still required.

4.3 Rail roughness monitoring

4.3.1 Monitoring frequency

If a large spread is considered unacceptable for the purpose of the prediction model, monitoring the rail roughness of the network is required to achieve a reasonably low calculation error. Than the question rises how often the network should be monitored.
To answer this question, it is necessary to know how rapidly the roughness can change. Rail roughness has been observed to vary with time, or more precisely speaking, vary with the amount of axle load passed. If an average noise level variation of 1 dB(A) due to rail roughness variation is allowed, it will be necessary to monitor at intervals of approximately 25 megatonnes ($25 \cdot 10^9$ kg) of axle load. This figure is based on a survey made in reference [8]. This amount of axle load passes on main passenger lines (5 trains per hour) every two years. On main freight tracks the required monitoring interval will be shorter than one year.

4.3.2 From average local roughness to average local noise creation levels

Once the average local roughness is known by monitoring, the accuracy of calculating the noise creation level is still limited by some unknown factors.

- *Contact patch size and position*. The contact patch is a difficulty that is not especially a problem when measuring roughness with a direct method. Also with indirect (axle-box vibration) measurements it has been shown that the wheels of the measurement train, do not run on the same patch every time they pass in the same spot. In many cases, the spread of roughness in lateral direction across the railhead is not so large [1].
- *Roughness level difference of both rails*. The left and right rail can be measured separately with direct methods. At some sites, the difference between right and left rail can be as large as 10 dB in a frequency band. It has been shown [9] that axle-box vibrations are influenced by the roughness of each of both rails, e.g. a high roughness level on the left-hand rail causes a raise at the right-hand axle box as well. Probably the total roughness of left and right rail must be added in the energy sense to represent track roughness.
- *Effective track length to be taken into account for noise calculation*. At a fixed receiver point, a certain length of the track will have a significant influence on the noise level. This length depends on the distance of the receiver point from the track. In general, this distance is estimated by four times the receiver distance. Therefore, the equivalent noise level can be represented by a value for roughness that represents a certain length of the track.

4.3.3 Rail roughness determination of a line or network

The ISO 3095 protocol is not suited to determine the (average or variation of the) rail roughness along a complete line or national railway network. As the rail roughness varies largely along the track, even if that track consists of one type of track construction (pad, rail, ballasted/slab), many measurement sites would be necessary.
For acoustical purposes, i.e. to assess or monitor the noise creation along the line, the desired measurement accuracy of rail roughness depends on the relative dominance of rail roughness in the total roughness. For example, if the wheel roughness of trains that dominate the noise creation is low, then the accuracy of measuring rail roughness should be high. This means that a general system that measures rail roughness for acoustic purposes requires high accuracy (within a few dB per octave band). Then, it can be advantageous to measure the noise creation itself instead of the rail roughness on a line. This is common practice now in Germany, where the *BüG* is operational. There, a measuring coach equipped with a microphone (in a reverberation box near the bogie) scans periodically a line which is appointed to be kept at a 3 dB lower noise

creation level than the reference level. The level of the running microphone is calibrated by stationary wayside microphone levels. Track sections that are above *reference* – 3 dB are marked for grinding.

4.3.4 Dwellings

It can be appropriate to restrict roughness monitoring and a special grinding regime to only those parts of the track or line that are in the vicinity of urban areas and dwellings.

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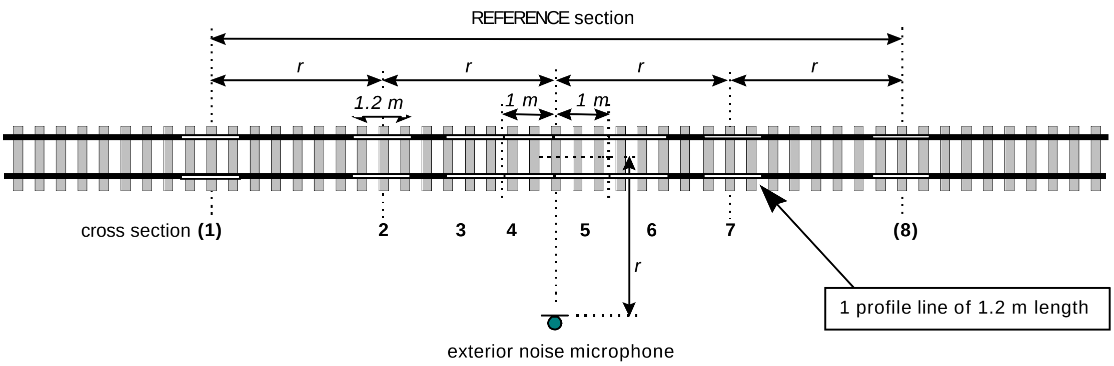
Appendix 1 Rail roughness measurement protocol

It is shown in reference [1] that the following protocol provides the same measurement accuracy as the original prEN ISO 3095:2001 protocol, but in less time and with a longer wavelength range for 1.2 m instruments:

- if one clear running band is visible, determine its width (see photograph); if the width is smaller than 30 mm, then it suffices to measure only one line on the rail under consideration;
- if the width exceeds 30 mm, or if two running bands are visible, then measure 2 (or 3) parallel lines at representative lateral positions of the rail under consideration. The position of the contact patch may become more certain if a piece of tape is stuck across the railhead before pass-by of the train of interest;
- in order to extend the spectral range, the two central sections “3” and “4” of the ISO-protocol are shifted 10 cm towards each other in order to obtain 20 cm overlap. Besides this, an additional section should be measured at either side of the two central ones, overlapping the central ones by 20 cm. Note that these additional sections are used only for long wavelength information. In cases where 2 (or 3) parallel lines should be measured, there is no need to measure these for the additional sections.
- The site average spectrum is found by averaging all measured lines energy wise. This yields a spectrum up to a wavelength of 10 cm (as before with the ISO-protocol). Next, the central sections (3 | 4 | 5 | 6) are processed according to a suitable concatenation procedure (e.g. see [1]) to provide additional information between 12.5 and 31.5 cm. These bands are used to extend the site average spectrum.
- For type testing purposes, all sections should be measured. Also for other purposes it is recommended that the full protocol be measured. In case of measurements on busy tracks, it is allowed to omit the outer sections 1 and 8. This protocol with only 6 sections will be called the *shorter protocol*.

An overview of this protocol is given in the Figure below. The omitted sections 1 and 8 for the shorter protocol are between parentheses.



New proposal for rail roughness measurement protocol for instruments of 1.2 m length.

Like the ISO standard protocol, this STAIRRS proposal does not explain how trolley systems should measure track sites. It has been proposed [11] to use continuous measurements in such cases.

Appendix 2 Wheel roughness measurement protocol

The instrument should contain a measurement probe that scans the relative excursion of the tread while the wheel is turned around. First, the centre of the running band on the wheel tread should be identified. In case of doubt, the middle of the wheel tread is taken as the centre of the running band. Then measure three parallel lines per wheel, and two wheels of one axle per vehicle. The lines should be either 10 or 20 mm apart, whatever is possible within the width of the shiny running band, see the figure below.
Measuring one wheel set per vehicle can give a sufficiently representative roughness characteristic for that vehicle. However, it should be made certain by visual inspection that all wheel sets show similar surface roughness.
For the assessment of the wheel roughness of trains consisting of more than 3 vehicles, the minimal requirement is to measure every other similar vehicle. Similarity is defined here with respect to function, brake type, wheel set type and maintenance regime. In case of multiple unit trains (typically without a loco), motored as well as non-motored axles should be measured. The average wheel roughness of a train is finally calculated by weighting the contributing spectra in correspondence with the occurrence of the vehicle types in that train.
The wavelength range should cover wavelengths up to 31.5 cm, like for rail roughness.

Pictures showing running bands and the choice of centre and off-centre lines.

Appendix 3 Processing of roughness data

This appendix treats general issues of data processing of roughness measurement methods. The focus is on direct methods, as these have common issues of concern. The processing of data from indirect roughness measurements is depending on the method itself and not described here.

General scheme for direct roughness processing

The way to transfer space-domain profile data into meaningful wavelength spectra appears not to be straightforward. A survey is given of the proposals for post-processing.

The general scheme of direct roughness data processing can be divided into two parts. One part is processing the spatial domain. The second part is the processing and presentation in the wavelength domain.

Spatial domain processing

The first step in this consideration should describe how the roughness profile is scanned by the probe. It is clear that any probe, in direct contact with the profile or not (e.g. inductive, laser), will have a finite scanning resolution (in longitudinal and transversal direction) limited by the width of the tip or beam. As a consequence of that, the probe's excursion is not a copy of the actual profile, see Figure 12a. As long as the probe's resolution is much smaller than the size of the wheel/rail contact patch, the distortion effects are negligible.

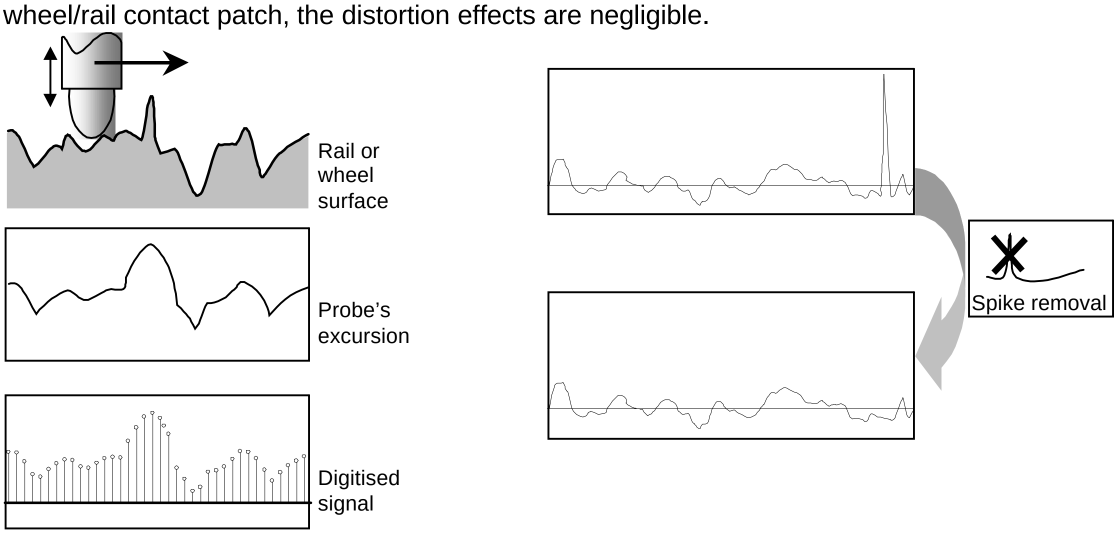


Figure 12a: Measurement. **b. Spike removal filter.**

The probe's excursion is then digitised (quantised). Before digitisation, the instrument should use a proper anti-aliasing filter[3]. If the probe's resolution exceeds the sampling distance, the anti-aliasing filter is not strictly required (see Figure 12a bottom). From this point, where a digital record is avialable, the analysis (signal processing) can start.

Step I. Begin and end of the signal are aligned by applying a tilt.
Step II. Spikes and pits that have been sensed by the probe are removed from the signal, as these will contaminate the spectrum, while they will not be occur in the actual wheel/rail contact, see Figure 12b.

---

[3] Note that the anti-aliasing filter will generally need to be part of the instrument. A lacking anti-aliasing filter before digitisation cannot be replaced by a high-pass filter after digitisation.

For **step II** different methods have been suggested. Report [3] proposes a non-linear filter that treats spikes and pits in the similar way. First, the spike detection threshold and the spike edge criterion are set. Second, the signal is scanned for spikes. Third, the edges from the spike are traced. Fourth, the signal part between the edges (i.e. the spike) is replaced by linear interpolation.

Paper [4] proposes a different approach for spikes and pits. Positive spikes are removed in a similar way as described above. Negative pits are removed by scanning the *signal* with a probe that has the same radius as a wheel, see Figure 13. In case wheel roughness is being analysed, the same algorithm can be applied.

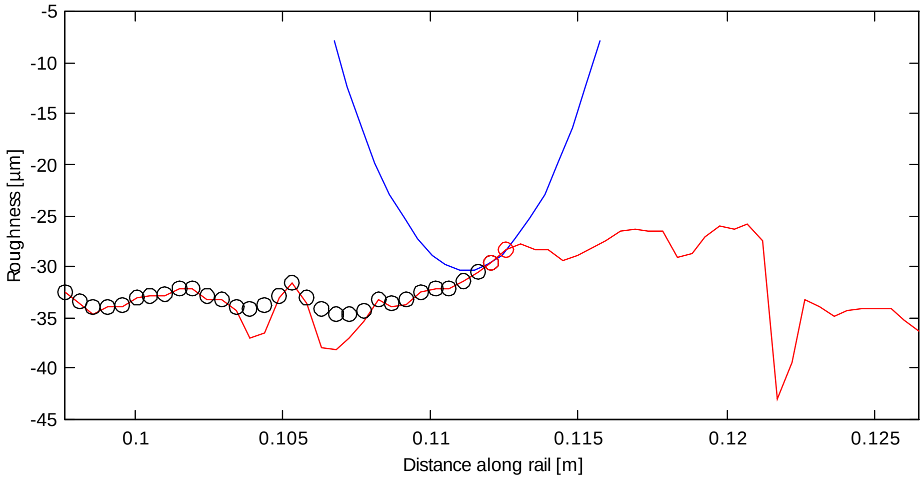


Figure 13: Pits removal according to method [4]. (red=original signal, dots=repaired signal, blue=wheel)

It is important to realise that method [3] and [4] mainly differ in the shortest wavelengths of the roughness spectrum. Figure 14 shows the average effect of applying method [4] rather than method [3]. The effect at 1 cm wavelength is only –0.5 dB.

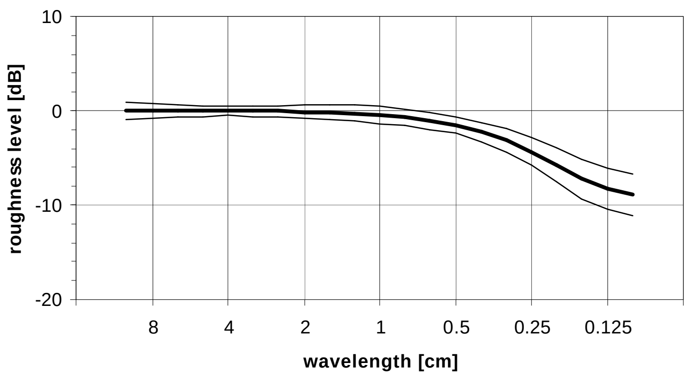


Figure 14: Average effect of spike removal method [4] relative to method [3]. Mean and spread of the difference for a set of 120 rail roughness lines (RM1200E) taken at various smooth and corrugated sites.

Producing a spectrum

The goal of the spectral analysis applied to the roughness signal is to produce a one-third octave power density spectrum. This can be achieved in two ways, via Fourier analysis or via band filtering. In either way the standard specifications for one-third octave band filtering should be respected [5]. Though these standard specifications are written for filtering in the time-frequency sense, they are easily applicable in the space-wavenumber sense by unit transfer ([s] $\rightarrow$ [m] and [Hz] $\rightarrow$ [m^{-1}]).

In general, the value for the longer wavelengths will be known with decreasing accuracy due to the finite signal length. In case Fourier analysis (e.g. FFT) is used, the accuracy is reflected in the number of narrow band lines that are found within a one-third octave band. It is common practice to limit the spectral range to those one-third octave bands that consist of 3 or more narrow band lines. The number of narrow band lines depends on the signal length. In case of measuring equipment with restricted length (typically1.2 m), it is therefore advantageous to apply the Fourier transform to the complete signal, rather than summing contributions from (overlapping) signal slices, see Figure 15.
In order to apply an FFT to the complete signal, a (space-domain) window should be applied. Different windows have been tested in [3]. It was found that a *hanning* window produces minor spectral leakage, however, throws away 50 % of the signal length. It is therefore proposed to use a so-called *tukey* window, which is a window composed of half an inversed cosine, a rectangular window and again half a cosine, see Figure 15. The length ratio of these three windows has been optimised with respect to maximum signal through-put and minimum spectral leakage to 5%, 90%, 5%.

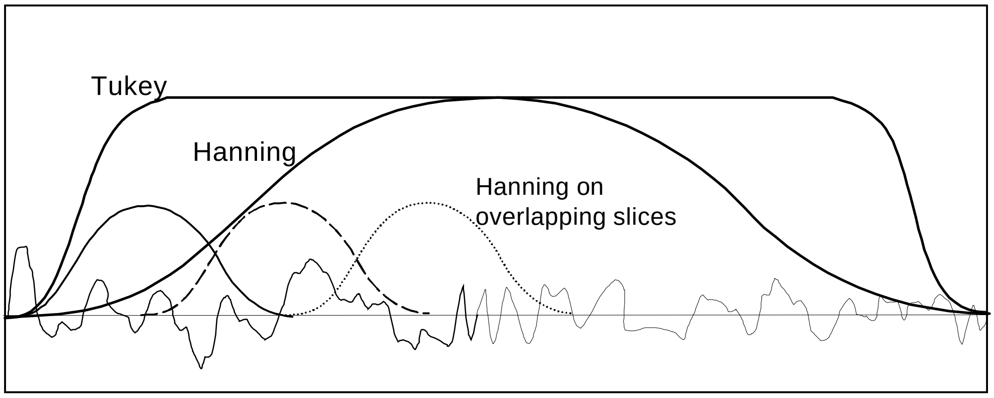
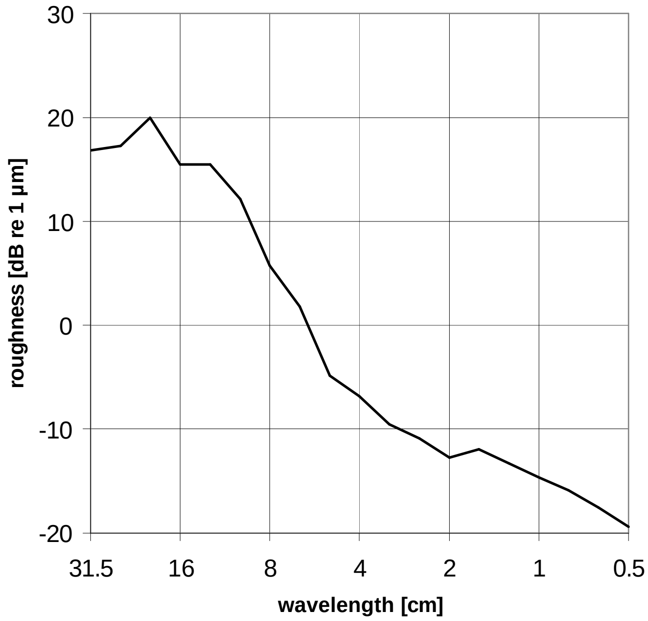


Figure 15: Figure windows

Note that for analysis of wheel roughness, **no** windowing is necessary as the first sample of the signal should coincide with, or actually adjoin, the last one.

Appendix 4 Presentation of roughness spectra

The roughness spectrum shows the dependency of the roughness level on roughness wavelength. The wavelength axis shows the wavelengths in reverse order: in fact, the wavenumber spectrum (unit: m^{-1}) is displayed here, but it is labelled with wavelength bands (unit [cm]) that are multiples of the decade 10, 8, 6.3, 5, 4, 3.15, 2.5, 2, 1.6, 1.25.
The reverse order of the wavelength axis enables direct comparison with noise spectra with frequency axis. The formula *frequency* = *speed* / *wavelength* applies here. For example, a train at a speed of 100 km/h feels a wavelength of 3 cm at a repetition rate (frequency) of 27.7 [ms^{-1}] / 0.03 [m] = 926 Hz.



wavelength	level
[cm]	[dB re 1µm]
31.5	16.8
25	17.3
20	20.1
16	15.4
12.5	15.4
10	12.1
8	5.8
6.3	1.8
5	-4.9
4	-6.9
3.15	-9.5
2.5	-10.9
2	-12.7
1.6	-12.0
1.25	-13.4
1	-14.7
0.8	-15.9
0.63	-17.6
0.5	-19.4

Figure 16: Standard presentation format of roughness.

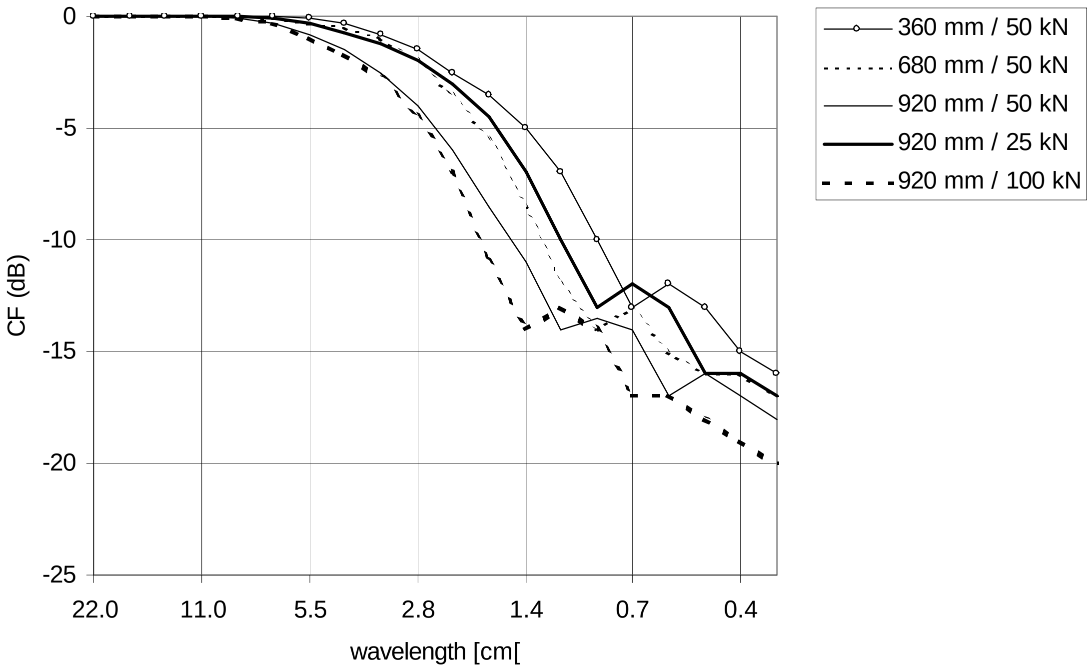
Features

- Wavelengths in descending order, ranging from 31.5 cm to 0.5 cm.
- Wavelength axis: values, marks and grid lines per octave. Values in [cm] with letters printed horizontally (upright). The following standard octave values are shown at the axis: 31.5, 16, 8, 4,2,1,.5. Preferably also marks (ticks) per one-third octave.
- Level axis: marks, values and grid lines per 10 dB. Ranging from –20 to 30 dB or more if appropriate.
- Aspect ratio 10 dB : 1 octave = 4 : 3.

A table with values is displayed to the side of the graph.

Appendix 5 Contact filter

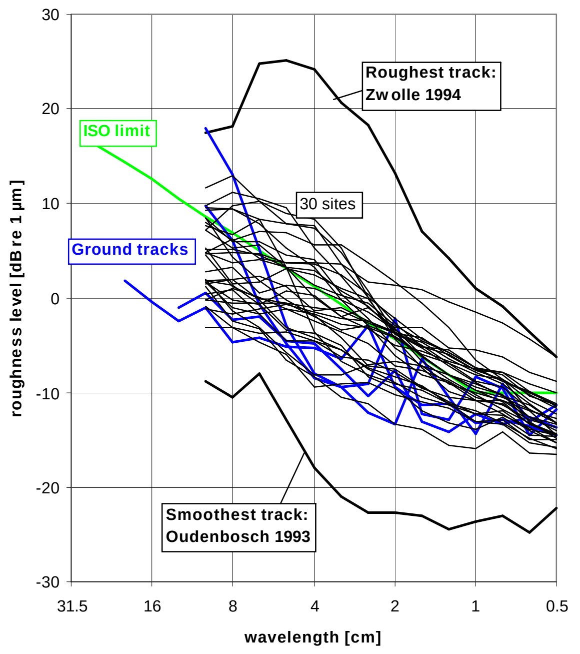
The total effective roughness can be derived from the added wheel and rail roughness by applying a suitable contact filter. The contact filter is a way to account for the filtering action of the wheel/rail contact patch. The excitation effect of wavelength that are shorther than the dimensions of the contact patch is attenuated.
The figure below demonstrates the dependency of the contact filter on wheel diameter and wheel load.



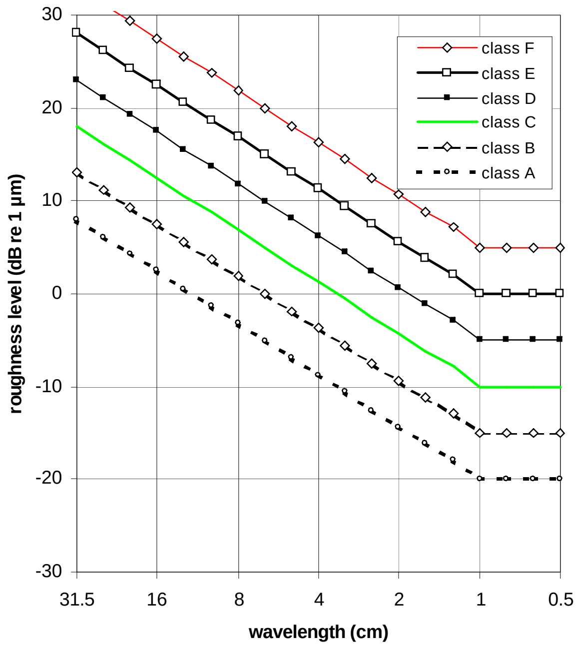
Contact filters, taken from [14].

Appendix 6 Rail roughness classification

The Danish draft version of the ISO 3095 standard [7] contains a proposal for rail roughness classification. The right-hand figure below shows this class system. The left-hand figure is a copy of Figure 7, redrawn here for clarity.



a. Examples and and range of rail roughness.



b: Classification based on offset ISO limits.

The class C limit curve is the limit from the ISO 3095:2001 draft. The other limit curves are constructed from the class C curve by adding or subtracting an offset (a multiple of 5 dB). The table below gives the rail roughness class limit spectra [dB re 1 µm].

wavelength [cm]	31.5	25	20	16	12.5	10	8	6.3	5	4	3.2	2.5	2	1.6	1.3	1	0.8	0.63	0.5
class F [dB]	33.0	31.1	29.3	27.5	25.5	23.7	21.9	19.9	18.1	16.3	14.3	12.4	10.6	8.8	6.8	5.0	5.0	5.0	5.0
class E [dB]	28.0	26.1	24.3	22.5	20.5	18.7	16.9	14.9	13.1	11.3	9.3	7.4	5.6	3.8	1.8	0.0	0.0	0.0	0.0
class D [dB]	23.0	21.1	19.3	17.5	15.5	13.7	11.9	9.9	8.1	6.3	4.3	2.4	0.6	-1.2	-3.2	-5.0	-5.0	-5.0	-5.0
class C [dB]	18.0	16.1	14.3	12.5	10.5	8.7	6.9	4.9	3.1	1.3	-0.7	-2.6	-4.4	-6.2	-8.2	-10.0	-10.0	-10.0	-10.0
class B [dB]	13.0	11.1	9.3	7.5	5.5	3.7	1.9	-0.1	-1.9	-3.7	-5.7	-7.6	-9.4	-11.2	-13.2	-15.0	-15.0	-15.0	-15.0
class A [dB]	8.0	6.1	4.3	2.5	0.5	-1.3	-3.1	-5.1	-6.9	-8.7	-10.7	-12.6	-14.4	-16.2	-18.2	-20.0	-20.0	-20.0	-20.0

Now the question of how to classify a certain track with known roughness needs to be answered. In the Danish proposal, a rail roughness spectrum belongs to the lowest class which it doesnot exceed at all. The prEN ISO 3095:2001 rule for site approval allows small exceedences. The consequences of these exceedences have not been investigated, but the idea is that a small exceedence in a spectrum that is elsewhere well below the limit, will not cause a higher noise level than a spectrum that lines up exactly with that limit. This rule is formulated in the text of the prEN ISO 3095:2001 standard in a slightly ambiguous way. Here, it is reformulated, and applied to the 6 classes of rail roughness.

The roughness class of a certain site is the **lowest** class (A is low, F is high) for which:

- none of the one-third octave bands exceeds the class curve;

or

- one one-third octave band exceed the class curve by less than 6 dB;

or

- two one-third octave bands exceed the class curve; one of them by less than 6 dB, the other by less than 3 dB;

or

- three one-third octave bands exceed the class curve; one of them by less than 6 dB, the other two by less than 3 dB. At least two of these bands must be adjacent;

or

- four one-third octave bands exceed the class curve; one of them by less than 6 dB, the other three by less than 3 dB. At least three of these bands must be adjacent.

If none of the above cases is valid for any class, the site class is set to class F.

For this example with 6 curves, the error in total roughness is estimated less than 2.5 dB, however for single one-third octave bands, the roughness can grow to 6 dB above the curve or it can be much more lower.
The error on the calculated noise creation will be less than 2.5 dB, and depends on the wheel roughness. Hereafter, it will be shown that for this example classification system, the noise level of consecutive classes differs less than 2 dB(A), reducing the error to less than 1 dB. This error does not include effects of limit exceedences as remarked earlier.

Combination of wheel and rail roughness and effect on noise levels

The roughness classes must be added (energy wise) in order to obtain the combined roughness of rail and wheel. The figure below shows the total roughness for three combinations:

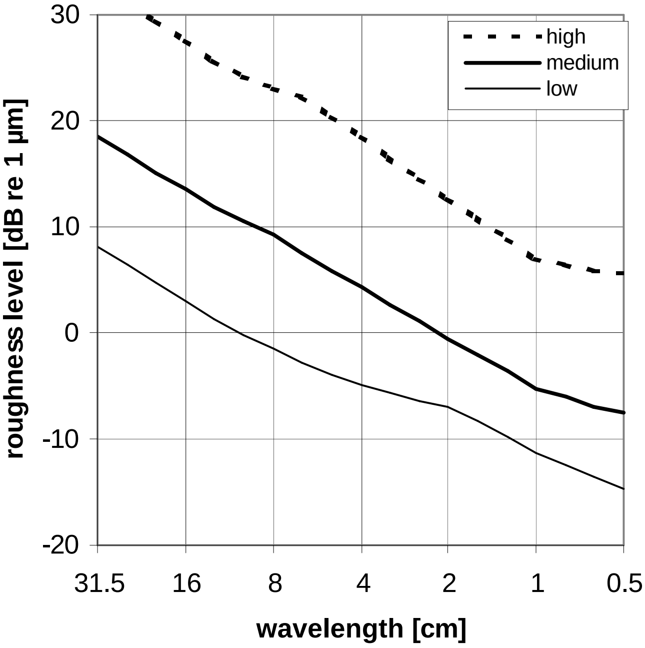
- lowest rail (A) and wheel (A) roughness
- medium rail (C) and wheel (B) roughness
- highest rail (F) and wheel (D) roughness.

The spread in noise level that can be achieved by combining the extreme classes is considerable. The difference between minimum and maximum noise level is approximately 23 dB(A). Medium level is about 9 dB(A) above low level, while high level is about 14 dB(A) above medium level[4].

An impression of the noise reduction steps that can result from the proposed classification system is obtained by considering the medium curve once more: rail class C (ISO-limit), wheel class B (disc-braked). Lowering the rail class to B yields a noise reduction of 1.7 dB(A). Also, lowering the wheel class to A yields a noise reduction of 2.4 dB(A).

Then, what noise reduction is possible according to this classification system by replacing cast-iron braking blocks (class C wheels) to appropriate K-blocks (class B wheels)? At medium rail roughness this implies a noise reduction of about 5 dB(A), while at class D rail roughness (one class above the ISO-limit) it will be about 3 dB(A).

[4] *Noise differences have been estimated as the average roughness level difference of the one-third octave bands between 10 cm and 1 cm, which corresponds with the dominant wavelength range at approx. 150 km/h.*



λ	low	medium	high
[cm]	[dB re 1 µm]		
31.5	8.2	18.4	33.0
25	6.4	16.7	31.2
20	4.7	15.1	29.4
16	3.1	13.6	27.6
12.5	1.4	11.9	25.7
10	-0.1	10.6	24.2
8	-1.5	9.3	22.9
6.3	-2.8	7.6	22.3
5	-4.0	5.9	20.4
4	-4.9	4.4	18.5
3.2	-5.7	2.7	16.6
2.5	-6.4	1.1	14.6
2	-6.9	-0.5	12.7
1.6	-8.4	-2.0	10.9
1.3	-9.7	-3.6	8.9
1	-11.4	-5.2	6.9
0.8	-12.5	-6.1	6.3
0.63	-13.7	-6.9	5.9
0.5	-14.7	-7.6	5.6

Combined roughness classes. ‘Low’ = wheel A + rail A. ‘Medium’ = wheel B + rail C. ‘High’ = wheel D + rail F.

Appendix 7 Single value indicator for roughness $L_{\lambda CA}$

Definition

The quantity $L_{\lambda CA}$ is a single value indicator for roughness. Its purpose is to quantify the roughness of wheel and rail in a number that is proportional to the noise level. The $L_{\lambda CA}$ is a weighted sum of a given roughness spectrum at a given train speed.

$L_{\lambda CA}$ is calculated as follows.

$$L_{\lambda CA} = 10 \log \sum_{\lambda = 20\,\text{cm}}^{0{,}4\,\text{cm}} 10^{\frac{1}{10}\{R(\lambda)+\Lambda(\lambda)+C(\lambda)+A(f(\lambda,v))\}} \quad \text{in [dB]}$$

with

$R(\lambda)$ the measured roughness spectrum as a function of the wavelength λ in [cm];

$\Lambda(\lambda) = -a\log(\lambda/\lambda_0)$ the lambda-filter in [dB], with λ_0 = 5 cm, a = 25;

The lambda-filter represents differentiating twice from roughness (=displacement) to acceleration (proportional to the excitation force via $F = m\,a$). For differentiating exactly twice, a =20; however a = 25 is used as an optimised value.

$C(\lambda)$ a contact filter, given by

$$C(\lambda) = 0 \qquad \text{for} \quad \lambda \geq 10^{8{,}5/10}$$

$$C(\lambda) = 10\log(\lambda) - 8{,}5 \qquad \text{for} \quad 10^{3{,}5/10} < \lambda < 10^{8{,}5/10}$$

$$C(\lambda) = 20\log(\lambda) - 12 \qquad \text{for} \quad \lambda \leq 10^{3{,}5/10}$$

$A(f)$ the A-weighting function, in which the frequency f is calculated from

$$f(\lambda, v) = \frac{v/3{,}6}{\lambda/100}$$

where v represents the train speed in [km/h].

Characteristics

- The combined $L_{\lambda CA}$ of wheel and rail is proportional with the rolling noise level. The combined $L_{\lambda CA}$ is calculated as the energy wise sum of the $L_{\lambda CA}$ of the wheels and rails.
- Roughness correction: if $L_{\lambda CA}$ and pass-by noise level L_{Aeq} at a certain site are known, it is possible to estimate the noise level for the same situation but with different roughness.
- $L_{\lambda CA}$ depends slightly on the train speed, as at different speeds other parts of the roughness spectrum become important. The A-weighting filter is responsible for the variation with train speed. The contact and lambda filter have some influence as well.
- The reference $L_{\lambda CA}$ = 0 dB is chosen arbitrarily, defined by the value of λ_0. Since the publication of the $L_{\lambda CA}$ method in 1997 [3], the value of λ_0 is fixed to 5 cm. This leads to the following typical values (at v = 120 km/h):

0 – 4 dB	"smooth rail"
5 – 7 dB	"ground rail" (approx. 1 month after grinding)
7 – 9 dB	average rail roughness (average of 30 Dutch sites [6])
10 –11 dB	"smooth wheels" (unbraked, disc-braked, or sinter blocks ([6]);
12 dB	average rail roughness of the Dutch network in calculation scheme [15];
14 –17 dB	corrugated rail;
18 –20 dB	"rough wheels" (cast-iron blocks, disc+additional cast iron blocks)
25 –28 dB	severely corrugated track