Bibliographical reference

The <italic>sonRAIL</italic> emission model for railway noise in Switzerland, T. Thron and M. Hecht, Acta Acustica **vol. 96** (Number 5), 2010, pp. 873-883

DOI
https://doi.org/10.3813/AAA.918346

Acta Acustica united with Acustica
Vol. 96 (2010) 873 – 883

DOI 10.3813/AAA.918346

The *sonRAIL* emission model for railway noise in Switzerland

T. Thron[1], M. Hecht[2]
[1] PROSE GmbH, 10555 Berlin, Germany. thomas.thron@prose-deutschland.de
[2] Technical University of Berlin, Dept. of rail vehicles, 10587 Berlin, Germany

Summary
In this article, the *sonRAIL* emission model for railway noise in Switzerland is presented. The model allows precise calculation of emission levels taking into account all relevant variables. The emission levels are determined as sound power spectra for five source heights. The rolling noise is calculated using roughness spectra for wheel and rail. Total rolling noise is sub-divided into track superstructure and vehicle components. The influence of different superstructure types is taken into account using transfer functions. The article explains the calculation procedures as well as the measurement procedures used to generate the model. A method of noise monitoring based on indirect roughness measurements is presented for the acquisition of model data.

PACS no. 43.50.Lj

1. Introduction

Traffic noise on railways is classified by the European Union as "annoying and damaging to health" [1] in the Directive on the Assessment and Management of Environmental Noise. It is estimated that over 10% of the population in Switzerland is affected by traffic noise, with the number affected at night twice that as affected by day [2]. Projections for the development in rail freight traffic indicate marked growth in future, so a further increase in noise levels in the already heavily used transit corridors can be expected [3].

Numerous national and international programmes to reduce noise are pursuing the goal of reducing the number of people affected by high noise levels due to transport. Currently favoured noise reduction measures include the construction of noise barriers and a programme to upgrade goods wagon braking systems from grey cast-iron brake blocks to composite K-blocks [4]. However, current noise models are unable to chart the effectiveness of these measures in relation to noise reduction with sufficient accuracy [5]. Effective and targeted application of the resources available for noise reduction therefore demand new and more accurate noise prediction models. For this reason, the *sonRAIL* project is being implemented by the Federal Office for the Environment (FOEN) [6]. This is a new calculation model for railway noise which is expected to clearly outperform the known models in terms of accuracy and reliability. The emission model presented here is a component of the overall *sonRAIL* model.

Received 18 December 2009,
accepted 19 April 2010.

2. Description of the emission model

2.1. Analysis of the existing emission models and *Semibel*

Different models are currently used to calculate noise emissions on railways; these are closely adapted to the national features of rail traffic. These models cannot therefore be adequately transferred to other countries or new vehicle types. A good overview of the existing calculation methods is provided by contributions [5], [7] and [8].

The preliminary investigations prior to the *sonRAIL* project indicated that the currently valid calculation model in Switzerland (*Semibel*) is subject to significant weaknesses regarding future noise predictions [9], [10]:

1. The emission levels for loud vehicles tend to be overestimated. For quiet vehicles the emission levels tend to be overestimated at high speeds in particular.
2. In most vehicle categories, the influence of speed is seen as the dominant source of error.
3. The effects of the track superstructure (superstructure type, routing parameters, and rail roughness) are for the most part lacking.
4. The calculations do not model frequency spectra.

Current calculations using *Semibel* [11] confirm the inaccuracies in the emission calculations which necessitate formulating a new calculation model for railway noise.

2.2. Components of a rolling noise model

Rolling noise is caused by unevenness (roughness) in the contact area between wheel and rail. Such roughness causes oscillations in both contact partners which are radiated via wheel, rail and sleeper as primary airborne noise. The objective of the research programmes *STAIRRS* [12],

Table I. Categories to describe rolling noise defined according to *STAIRRS*.

	Obtained quantities			Applications and notes
	Total	Vehicle	Track	
Level 0 (no separation)	$L_{W,roll}$	–	–	Overall levels, large spread
Level 1 (sound separation)	$L_{W,roll}$	$L_{W,veh}$	$L_{W,tr}$	For assessing track or vehicle noise control measures
Level 2 (sound and roughness separation)	$L_{W,roll}$	$L_{r,veh}$, $L_{HW,veh}$, $L_{W,veh}$	$L_{r,tr}$, $L_{HW,tr}$, $L_{W,tr}$	For independent characterization of tracks and vehicle
Level 3 (sound, roughness and dynamics separation)	$L_{W,roll}$	$L_{r,veh}$, $L_{HW,veh}$, $L_{W,veh}$, contact forces	$L_{r,tr}$, $L_{HW,tr}$, $L_{W,tr}$, contact forces	Partly using calculation, when vehicle not available

METARAIL [13] and *IMAGINE* [14] was to describe the complex relationships in the generation of rolling noise using measurement standards and to allow determination, using metrology, of all the necessary model parameters. In *STAIRRS* four stages of emission measurements are defined for this purpose; Table I.

In Level 0 only pass-by levels are recorded as microphone measurements; separation of rolling noise with consideration of roughness is not possible. In Level 1, individual sound sources can be recorded using appropriate measurement methods (array measurement), though again without consideration of wheel and rail roughness. In Level 2, on the other hand, calculation of rolling noise $L_{W,roll,i}$ as a function of wheel and rail roughness as well as separation of rolling noise into a vehicle component $L_{W,veh,i}$ and a track component $L_{W,tr,i}$ is possible [15]. The radiation properties of vehicle and track superstructure are described by the transfer functions $L_{HW,veh,i}$ and $L_{HW,tr,i}$. The transfer functions are determined by the emission level and the effective total roughness $L_{r,tot,i}$. The effective total roughness can be determined by direct measurement of wheel roughness $L_{r,veh,i}$ and rail roughness $L_{r,tr,i}$ or by an indirect measurement method. In the case of a direct measurement, the effect of the contact filter $A_{3,i}$ in wheel-rail contact must be taken into consideration. This describes, in simplified form, how the roughness in the contact area leads to generation of oscillations in both wheel and rail [16], [17]. In Level 3, additional information on the forces in the wheel-rail contact is needed. These parameters, however, can be determined only by corresponding simulation programs (e.g. *TWINS*).

In the *sonRAIL* emission model, Level 2 is replaced by STAIRRS, as here all essential parameters for accurate description of rolling noise are taken into account and can be determined by measurements. Consequently, the chosen model structure meets the recommendations of the European Commission for a modern calculation model for railway noise [18].

2.3. Database for creating the model

In accordance with the guidelines, most model parameters were determined by measurements. To this end, from 2007 to 2009, extensive measurements were made on the Swiss rail network and on vehicles. This procedure demonstrated that the model parameters accurately simulate the actual, acoustic state of vehicles and the rail network. The measurements included both acoustic pass-by measurements for speeds up to 200 km/h and measurements using a vertical microphone array to record source distribution. In addition, wheel and rail roughness, Track Decay Rate and local sound propagation conditions were recorded as parameters which substantially influence rolling noise [19, 20].

3. Description of sources

3.1. Structure of the emission model

In accordance with the prior considerations on selection of an appropriate model structure and the Swiss Federal Office for the Environment‘s *sonRAIL* specification plan [21], the result is a model structure which in terms of the essential core areas is consistent with the *IMAGINE* emission model.

The *sonRAIL* emission model calculates sound power spectra $L_{W,hkpi}$ between 100 and 8000 Hz for five source heights. In the emission model, a distinction is made between primary sources (rolling noise) and secondary sources (traction unit and set noise). The primary sources are calculated using effective roughness and transfer functions. The calculation of secondary sources is performed using a base value and a speed-dependent function. The selected source heights were chosen according to the heights in the *IMAGINE*model and are shown in Figure 2. A distinction is made between eleven vehicle categories, for which all model parameters are provided. Situations like curve and break sqeal and sound propagation from shunting yards are not included in the modell.

3.2. Rolling noise

Rolling noise is calculated separately for track $L_{W,tr,i}$ and vehicle $L_{W,veh,i}$. On the basis of the effective total roughness in wheel-rail contact $L_{r,tot,i}$ vehicle and track transfer functions $L_{HW,veh/tr,i}$ are used to calculate rolling noise, taking into account the number of axles N_{ac},

$$L_{W,tr,i} = L_{r,tot,i} + L_{HW,tr,i} + 10 \lg N_{ac}, \tag{1}$$

$$L_{W,veh,i} = L_{r,tot,i} + L_{HW,veh,i} + 10 \lg N_{ac}. \tag{2}$$

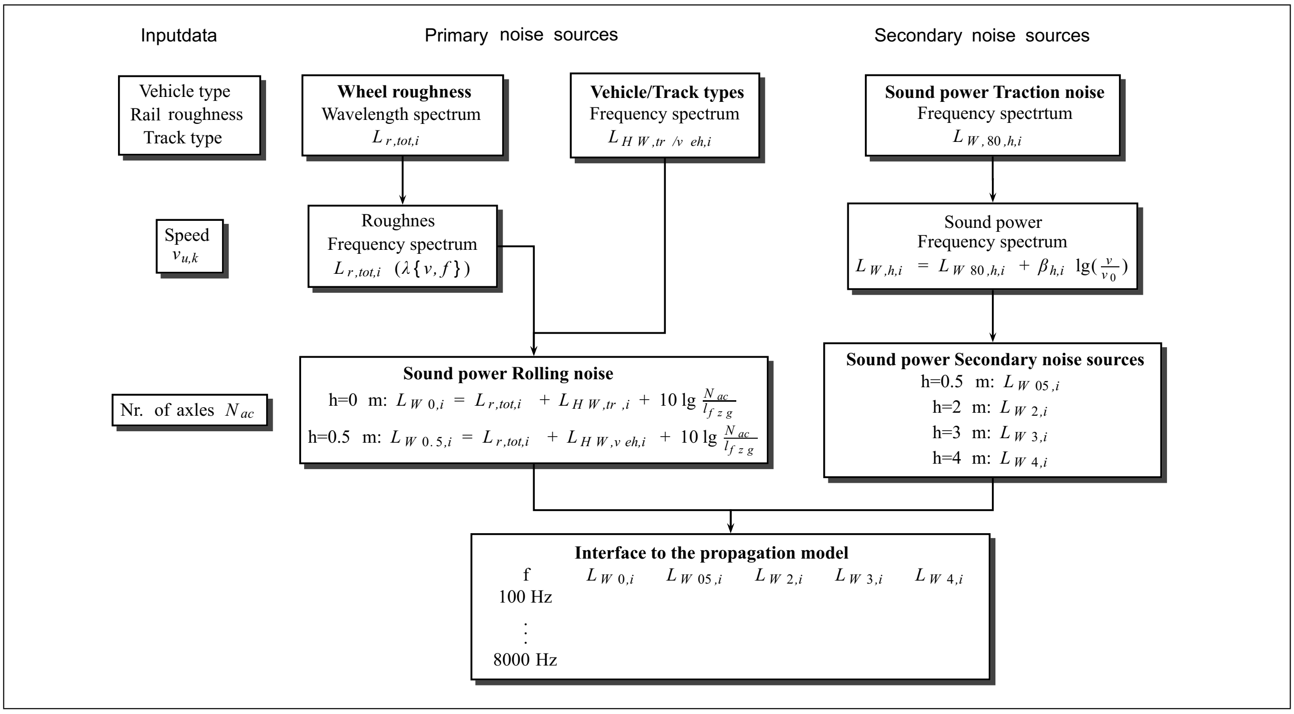

Figure 1. Diagram showing the procedure for calculating emissions for primary and secondary sources.

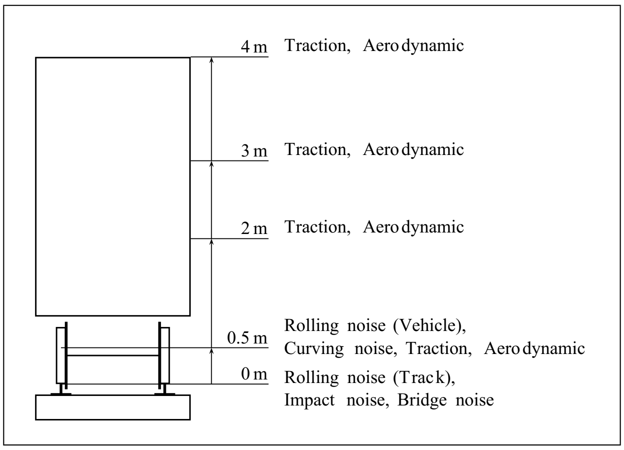

Figure 2. Noise sources p and their typical distribution into source heights.

The total rolling noise is calculated from the track and vehicle components,

$$L_{W,roll,i} = L_{W,tr,i} \oplus L_{W,veh,i}, \tag{3}$$

where the operator $\oplus$ is used to signify the energy sum.

Roughness is specified as a function of wavelength λ. Conversion from wavelength to frequency and vice versa is performed by accounting for speed v,

$$\lambda(v, f) = \frac{v}{f} \text{ und } f(v, \lambda) = \frac{v}{\lambda}. \tag{4}$$

The effective total roughness $L_{r,tot,i}$ is calculated for a known wheel and rail roughness $L_{r,veh/tr,i}$, using the contact filter $A_{3,i}$,

$$L_{r,tot,i}(\lambda) = (L_{r,veh,i} \oplus L_{r,tr,i}) + A_{3,i} \tag{5}$$

Furthermore, the effective total roughness $L_{r,tot,i}$ can be determined by measurement using the relationship

$$L_{r,tot,i}(f_i) = L_{aeq,i} - A_2 - 40\lg(2\pi f_i) - 10\lg\left(8.686\frac{N_{ac}}{l_{veh}D_{s,i}}\right). \tag{6}$$

The roughness spectra used in the emission model were acquired in an extensive series of measurements of sections of Swiss railways and rail vehicles. Wheel roughness values $L_{r,veh,i}$ are shown in Figure 3 and are allocated to each vehicle category as permanent vehicle parameters:

1. D-braked: vehicles with wheel or axle disc blocks
2. K-braked: vehicles with composite brake blocks
3. Ci-braked: vehicles with cast iron brake blocks

In accordance with the test results, separate roughness spectra are specified for some traction vehicles.

Rail roughness in the undisturbed rail $L_{r,tr,i}$ are shown in Figure 4 and are sub-divided into 3 categories using the roughness level $L_{\lambda,CA}$:

1. smooth rail roughness $L_{\lambda,CA} < 4\,\mathrm{dB(A)}$
2. average rail roughness $4 \leq L_{\lambda,CA} \leq 10\,\mathrm{dB(A)}$
3. bad rail roughness $L_{\lambda,CA} > 10\,\mathrm{dB(A)}$

$L_{\lambda,CA}$ is a weighted sum of a roughness spectrum at a given speed. The purpose of $L_{\lambda,CA}$ is to quantify the roughness of wheel and rail in a number that is proportional to the noise level [22].

The transfer functions required for calculation of sound radiation are shown in Figures 5 and 6. A distinction is made between the following track superstructures:

1. concrete monobloc sleepers with UIC54 and UIC60 rails
2. concrete bi-block sleepers with UIC54 rails

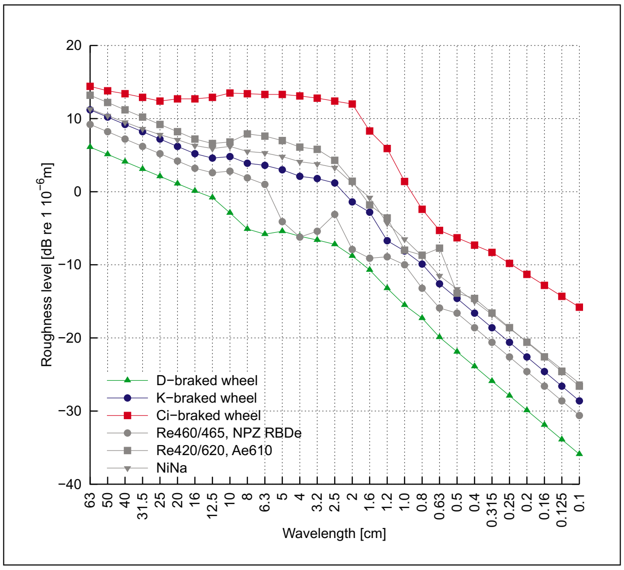

Figure 3. Standard values for direct wheel roughness.

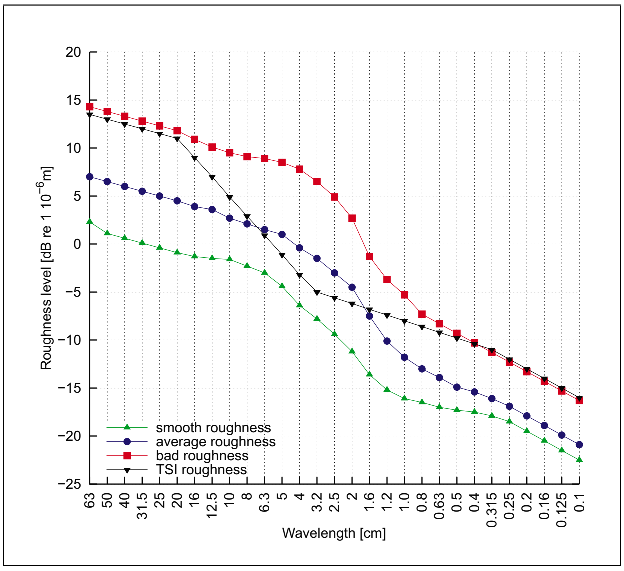

Figure 4. Standard values for direct rail roughness

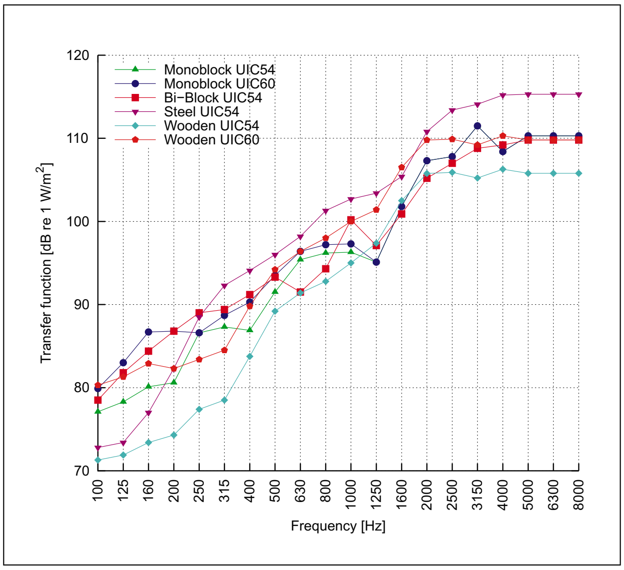

Figure 5. Standard values for track transfer functions.

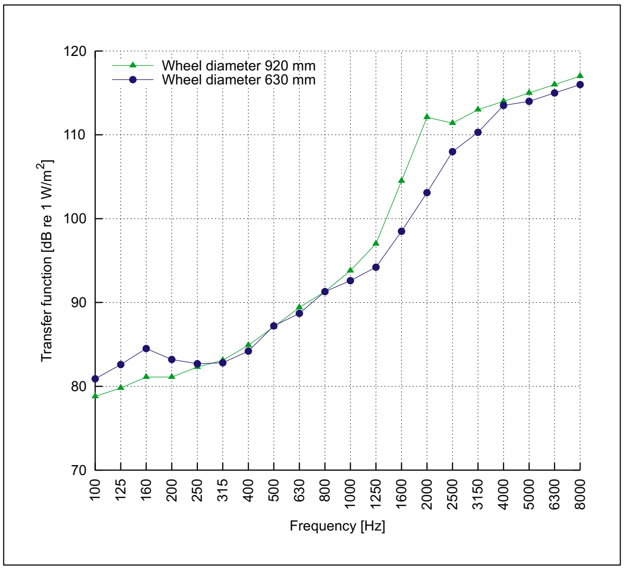

Figure 6. Standard values for vehicle transfer functions.

3. wooden sleepers with UIC54 and UIC60 rails
4. steel sleepers with UIC54 rails

3.3. Curves

The influence of track curves on vehicle emission characteristics for rolling noise is described by the equivalent wheel roughness $L_{r,crv,i}$:

$$L_{W,curve,i}(h_{0\,\mathrm{m}}) = L_{r,tot,i} + L_{HW,tr,i} + 10\lg N_{ac} \quad (7)$$

$$L_{W,curve,i}(h_{0.5\,\mathrm{m}}) = L_{r,tot,i} + L_{HW,veh,i} + 10\lg N_{ac} \quad (8)$$

$$L_{r,tot,i} = \left[L_{r,tr,i} \oplus L_{r,veh,i} \oplus \left(L_{r,crv,i} - \gamma \lg \frac{R}{R_0}\right)\right] + A_{3,i}. \quad (9)$$

The influence the radius of a bend is taken into consideration as a function of the equivalent wheel roughness of a vehicle:

$$\gamma = \begin{cases} 15.0 & : \quad \text{Equivalent roughness: smooth} \\ 30.0 & : \quad \text{Equivalent roughness: bad} \end{cases} \quad (10)$$

The reference radius is $R_0 = 500\,\mathrm{m}$. A section of track is defined as a curve if its radius is less than 1000 metres. The factor γ depends on the roughness category of the equivalent wheel roughness of the respective vehicle type and takes into consideration the curve running behaviour of a vehicle type. Using the different values for γ the measurement results take into account the fact that for vehicles with poor curve running behaviour the dependence on the curve radius is more pronounced. Curve sqeal is not included, due to the much more complicated situation of running behaviours. The presented description of the emission calculation based on measurements. For the

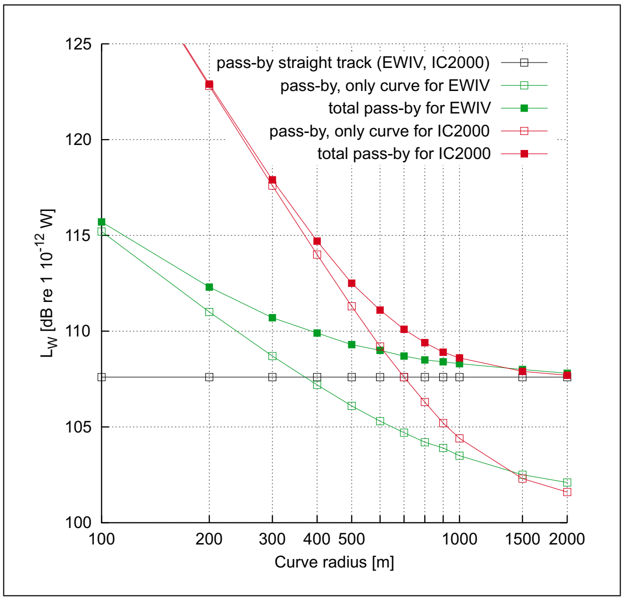

Figure 7. Graphical representation of equation (9) for calculation of emission levels in rail curves with low rail roughness.

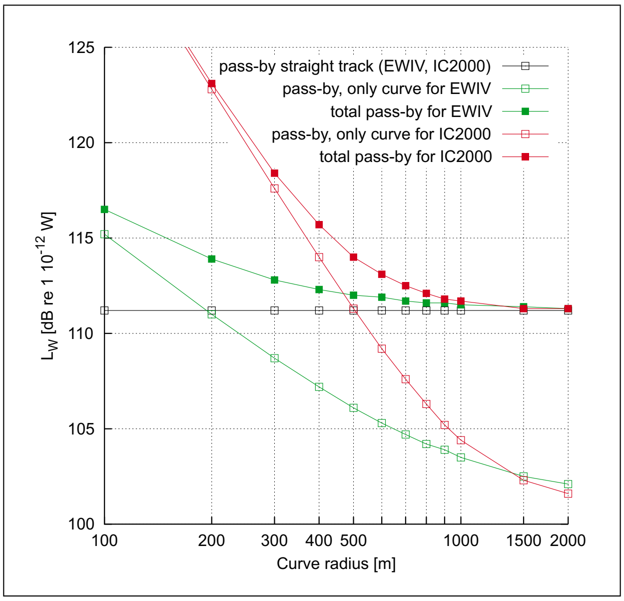

Figure 8. Graphical representation of equation (9) for calculation of emission levels in rail curves with high rail roughness.

description of curve sqeal also simulation modells should be included in the emission model.

Figures 7 and 8 show the relationships according to equation (9) for EWIV vehicles (equivalent roughness: smooth) and IC2000 vehicles (equivalent roughness: bad) for two different rail roughness values. Because of the better curve running behaviour of the EWIV vehicles, in the curve with low rail roughness the influence of curve running only dominates the emission level for $R < 400\,\mathrm{m}$. In the case of the IC2000 vehicles, the effects of curve running dominate below a bend radius of $R < 700\,\mathrm{m}$. For curved sections with high rail roughness, rolling noise dominates even for smaller bend radii. In the case of EWIV vehicles, the effects of curve travelling are discernable only for $R < 200\,\mathrm{m}$ and for IC2000 vehicles for $R < 500\,\mathrm{m}$. These considerations also hold for vehicles with high wheel roughness.

3.4. Switches

The emission levels at a discontinuity (switch, rail joint) are modelled using equivalent wheel roughness values $L_{r,tr,impact,i}$. According to the definition of the propagation model relating to constant emission values, each points crossing area is modelled as a separate section of track one metre in length:

$$L_{W,impact,i}(h_{0\,\mathrm{m}}) = L_{r,tot,imp,i} + L_{HW,tr,i} + 10 \lg N_{ac}, \quad (11)$$

$$L_{r,tot,imp,i} = (L_{r,tr,impact,i} \oplus L_{r,veh,i}) + A_{3,i}, \quad (12)$$

$$L_{W,impact,i}(h_{0.5\,\mathrm{m}}) = L_{r,tot,i} + L_{HW,veh,i} + 10 \lg N_{ac}, \quad (13)$$

$$L_{r,tot,i} = (L_{r,tr,i} \oplus L_{r,veh,i}) + A_{3,i}. \quad (14)$$

3.5. Bridges

The influence of different bridge types is taken into consideration using frequency-dependent level supplements $L_{W,bridge,i}$ at source height 0 m for the following bridge categories:

1. Solid and reinforced concrete bridges with ballast track structure
2. Steel bridges with ballast track structure
3. Steel bridges without ballast track structure

These categories are sub-divided into additional bridge types for the default values which are provided. The calculation is made according to

$$L_{W,tr,i} = (L_{r,tot,i} + L_{HW,tr,i} + 10 \lg N_{ac}) \oplus L_{W,bridge,i}, \quad (15)$$

$$L_{W,veh,i} = L_{r,tot,i} + L_{HW,veh,i} + 10 \lg N_{ac}. \quad (16)$$

3.6. Traction noise

The secondary emission levels are related to the reference speed $v_0 = 80\,\mathrm{km/h}$ and are calculated for each source height h in frequency band i of vehicle category k,

$$L_{W,sec,hki} = L_{W80,hki} + \beta_{hki} \lg\left(\frac{v}{v_0}\right). \quad (17)$$

β_{hki} represents the frequency-dependent factor.

The base value $L_{W80,hki}$ and β_{hki} are specified for each vehicle category. In the case of driven vehicles, a distinction can be made between operating conditions at average or pronounced source power. In addition to the specified secondary sound powers, the standard values of the IMAGINE model can also be used. In [14] and [23]–[26] the IMAGINE model for secondary noise on rail vehicles is explained in detail. These data also include values for vehicles with combustion engines and other electric vehicles. Values are given for standstill, constant speed and start-up under load. When the data are integrated into the *sonRAIL* model it must be ensured that the sound pressure levels L_{peq} specified in tabular form in [27] are converted into sound power levels.

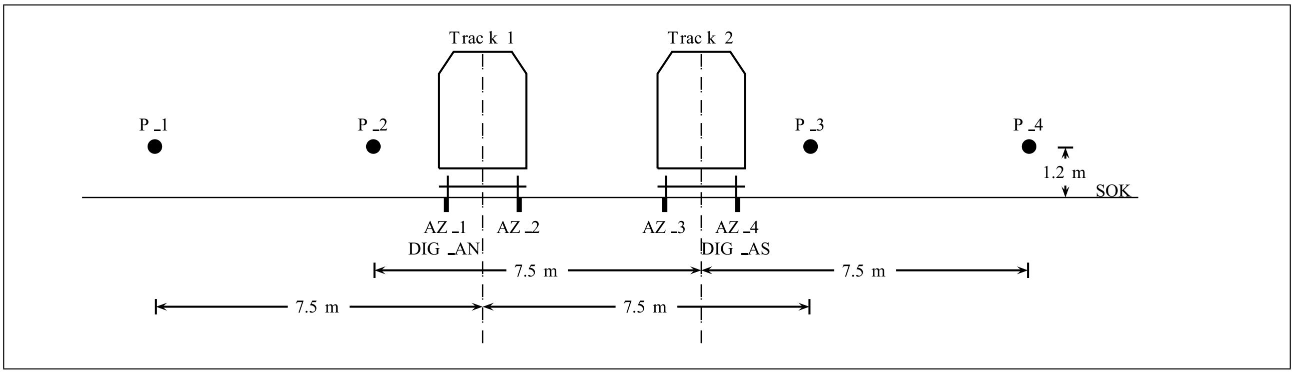

Figure 9. Measurement point plan on a two-track section to EN 3095 for recording all *sonRAIL* model parameters.

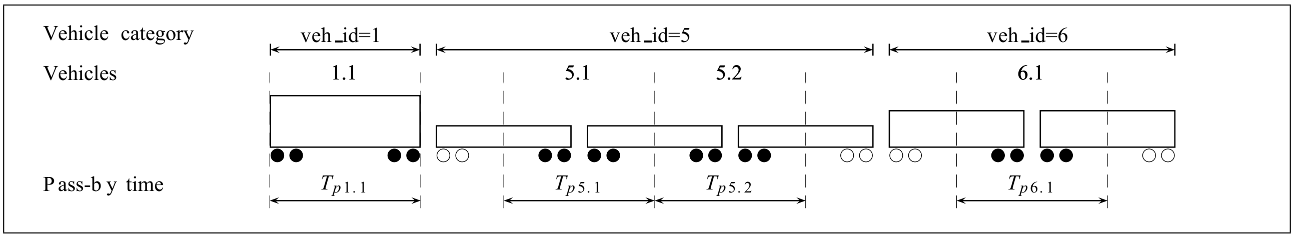

Figure 10. Schematic representation of the evaluation of a train set with discretisation into vehicle categories.

3.7. Aerodynamic noise

In addition to traction noise, an aerodynamic noise component can be taken into account in the emission model. This is described for a source height h of vehicle category k and third octave frequency i using the following relationship:

$$L_{W,aero,hki} = L_{W200,hki} + \delta \lg\left(\frac{v}{v_1}\right), \qquad (18)$$

with the reference speed $v_1 = 200\,\mathrm{km/h}$ and the frequency-independent factor $\delta = 60$. This value is used as a default; it is independent of the vehicle category k, source height h and the frequency band i.

4. Measurement methods and data acquisition

Determination of all model parameters using measurement techniques can be performed in accordance with current standards, so that a reproducible database is achieved for creating the model. The acoustic pass-by measurements are carried out to EN 3095 [28]. Direct measurement of rail roughness is carried out according to TSI Noise or EN 15160 [29] respectively, and the track decay rate to EN 15461 [30]. Figure 9 shows the measurement set-up used on a two-track section within the *sonRAIL* emission measurements. Each measurement point is equipped with four microphones $P_{1...4}$ each at a distance of 7.5 m from the centre of the track, and with an acceleration sensor at the rail foot A_Z. An axle detector DIG was installed in the measurement cross-section on each track.

The calculation of the model parameters is performed for each vehicle of a pass-by. Each vehicle in a train set is accurately determined by the first n_{anf} and last axle n_{end} using the axle detector signals. Pass-by duration T_p is then determined as a function of the pass-by speed v and the vehicle length l_{veh}. Clipping of the microphone and acceleration signals from the total signals takes place in the centre of the vehicle in each case. In the case of traction vehicles the pass-by duration is determined from buffer to buffer. Figure 10 illustrates this method.

4.1. Transfer functions

The transfer functions of all measured vehicles and of the track type in the measurement cross-section can be determined using the measurement set-up as described and the subsequent data processing. To this end the total transfer function $L_{HW,tot,i}$ $\left[\mathrm{dB\ re\ 1\ W/m^2}\right]$ is calculated from the sound power spectra of the rolling noise source $L_{W,roll,i}$ and the effective roughness $L_{r,tot,i}$ of rail aligned towards the microphone:[1]

$$L_{HW,tot,i} = L_{W,roll,i} - L_{r,tot,i} - 10 \lg N_{ac}. \qquad (19)$$

If the reference transfer function at a measurement point $L_{HW,ref,i}$ is known, the transfer functions of the track $L_{HW,tr,i}$ and vehicle $L_{HW,veh,i}$ can be calculated. If $L_{HW,tot,i} - L_{HW,ref,i} \geq 1$ dB the transfer functions can be calculated,

$$L_{HW,veh,i} = L_{HW,tot,i} \ominus L_{HW,ref,i}, \qquad (20)$$

$$L_{HW,tr,i} = L_{HW,ref,i}, \qquad (21)$$

[1] Specification of the transfer functions can also be determined analogously with the sound pressure signals: $L_{Hp,tot,i} = L_{p,tot,i} - L_{r,tot,i} - 10 \lg \frac{N_{ac}}{l_{veh}}$ $\left[\mathrm{dB\ re\ 20\,\frac{Pa}{\sqrt{m}}}\right]$

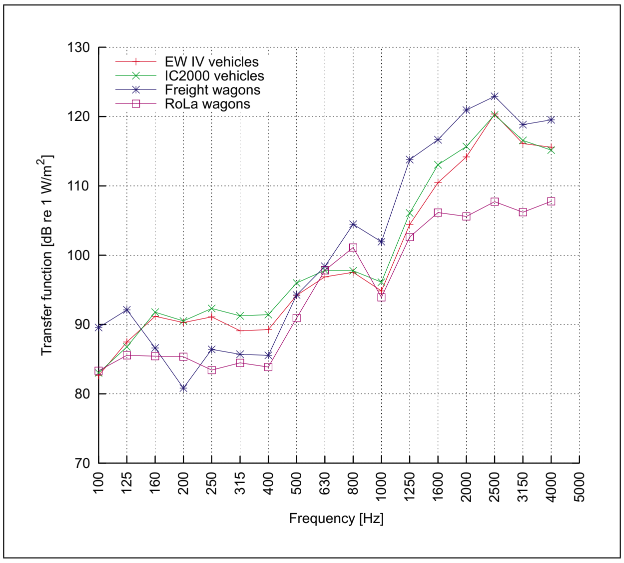

Figure 11. Total transfer functions for different vehicle categories for determination of a reference vehicle.

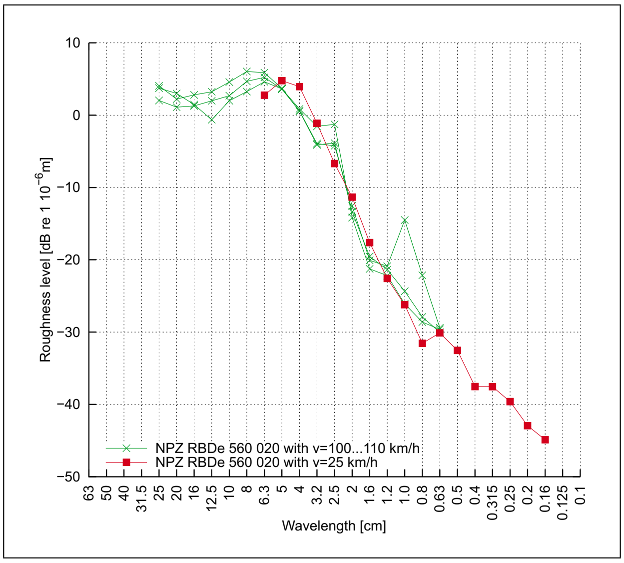

Figure 12. Indirectly measured, effective total roughness for test journeys of a local train at different speeds.

otherwise the following approximation should be used:

$$L_{HW,veh,i} = L_{HW,tot,i} - 7\,\mathrm{dB}, \tag{22}$$

$$L_{HW,tr,i} = L_{HW,ref,i} - 1\,\mathrm{dB}, \tag{23}$$

where the operator $\ominus$ is used to signify the energy difference.

The reference transfer function $L_{HW,ref,i}$ corresponds to the total transfer function of a reference vehicle and describes the acoustic radiation behaviour of the track structure type. In this way the total rolling noise can be divided into a track component and a vehicle component in the emission model. This procedure was developed in the *METARAIL* project [13]. The reference transfer function is determined from pass-bys of vehicles which radiate a very small proportion of rolling noise in comparison to the track structure. This can be achieved by using vehicles with small wheel diameters and a light or well-decoupled vehicle structure. If such a vehicle is recorded during a pass-by using measurement technology, it can be assumed that the measured pass-by level will be dominated by the rolling noise radiated by the track structure. By calculating the transfer function between effective total roughness and the pass-by level, the reference transfer function can be determined. The RoLa and NiNa vehicles in particular are recommended as suitable vehicles for this method.

Figure 11 shows the measured total transfer functions $L_{HW,tot,i}$ for various vehicle categories. Distinctly lower transfer functions are measured on the RoLa vehicles in comparison with the other vehicles for frequencies over 1000 Hz. In the lower frequency range, the transfer functions of all vehicles are similar. In this low frequency range, the radiation behaviour is therefore independent of the vehicle type and track structure radiation dominates. At higher frequencies the radiation of the vehicles begins to dominate. Since in the case of the RoLa vehicles no significant radiation can originate from the vehicle structure, correspondingly lower transfer functions are calculated. These vehicles are therefore particularly good as reference vehicles.

4.2. Determination of roughness on individual vehicles

The effective total roughness $L_{r,tot,i}$ can be determined when the wheel and rail roughness are known by using the contact filter $A_{3,i}$ according to equation (5). The roughness of both contact partners are summed in terms of energy; the contact filter takes into account the fact that short wavelengths which are located within the contact area have little influence on rolling noise. However, this method is unsuitable for determining effective roughness on a large number of vehicles, as direct measurement of wheel roughness is a very time-consuming procedure [19].

On the other hand, the indirect measurement method according to equation (7) offers the possibility of making a large number of effective roughness measurements. The vertical rail foot accelerations are recorded during the passage of a vehicle or train. If the Track Decay Rate $D_{s,i}$ is known, the effective roughness can be determined directly and converted into a wavelength spectrum using the pass-by speed according to equation (4). The effective roughness values are standardised to the axle density N_{ac}/l_{veh}, i.e. to the number of axles, which make a contribution to the vertical rail accelerations and the length of the vehicle being evaluated. A_2 describes the relationship between rail foot acceleration and the resulting effective total roughness. In [31] standard values for A_2 are specified as a function of pad stiffness. In Figure 12 the indirectly measured, effective total roughness values are shown for the passage of a local train at a measurement point with a pass-by speed of $v = 25\,\mathrm{km/h}$ and $v = 100\ldots110\,\mathrm{km/h}$. From the results it is evident that the wavelength range which can be evaluated is a function of the speed of travel and

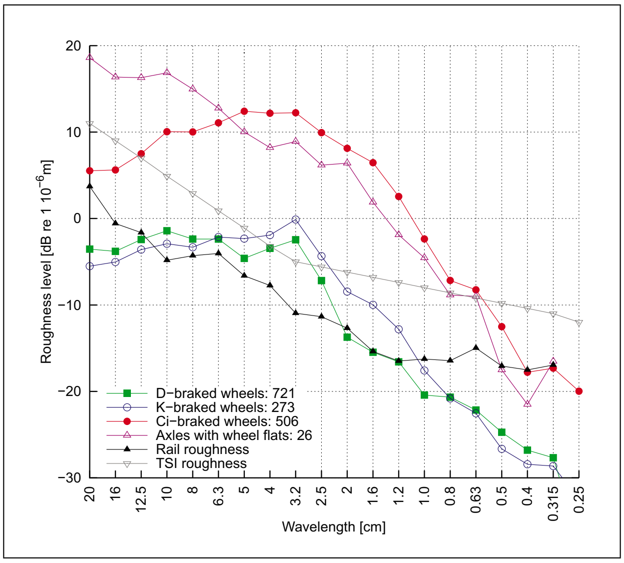

Figure 13. Indirectly measured wheel roughness on the Basel – Olten rail route for different vehicle categories.

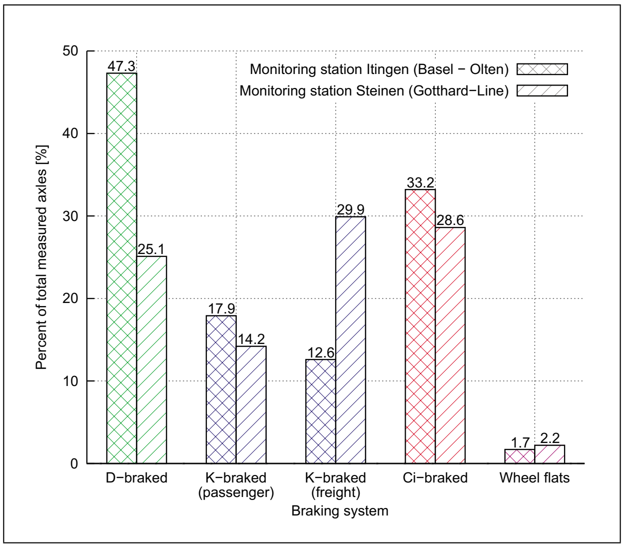

Figure 14. Percentage distribution of wheel roughness for correct representation of the traffic mix on the Basel – Olten rail route.

therefore it is desirable to obtain as large a range of travel speeds as possible.

4.3. Measurement of wheel roughness at monitoring stations

Indirect roughness measurements on individual vehicles is well suited to describing rolling noise. However, for accurate emission calculations within the *sonRAIL* model, there is a requirement for the wheel roughness spectra of vehicles travelling over a route or a section of a route. These data can be acquired in monitoring stations. The wheel roughness values of each wheel of a vehicle are recorded using the indirect method. Within the model, the emission level can be calculated for each individual vehicle using rail roughness values. In addition, an average wheel roughness can be determined for each vehicle category and stored in the model. Wheel roughness values are calculated according to

$$L_{r,tot,dir}(\lambda) = L_{r,tot,i}(\lambda) - A_3(\lambda) \quad \left[\text{dB re } 1\ 10^{-6}\text{m}\right]. \quad (24)$$

If $L_{r,tot,dir}(\lambda) - L_{r,tr,i}(\lambda) \geq 1$ dB the wheel roughness can be calculated as

$$L_{r,veh,i}(\lambda) = L_{r,tot,dir}(\lambda) \ominus L_{r,tr,i}(\lambda), \quad (25)$$

otherwise the following approximation should be used:

$$L_{r,veh,i}(\lambda) = L_{r,tot,dir}(\lambda) - 7\,\text{dB}, \quad (26)$$

$$L_{r,tr,i}(\lambda) = L_{r,tot,dir}(\lambda) - 1\,\text{dB}. \quad (27)$$

Figure 13 shows the results of monitoring on the Basel – Olten rail route in Switzerland. In total, roughness values were determined on ≈1500 axles. The representation shows the roughness spectra of disc-braked, K- braked and grey cast iron-braked vehicles, the roughness of vehicles with flat points and the rail roughness determined directly in the measurement cross-section. These roughness spectra are assigned to the route section and can be used for emission calculations. The additional evaluation of the distribution of the different roughness categories permits an accurate description of the traffic mix. Figure 14 shows the results on the Basel – Olten route and on the Gotthard route. This information is of great interest especially with regard to emission calculations for freight trains, as correct sub-division into vehicles with grey cast iron and K brakes is now possible.

4.4. Measurement of rail roughness using a monitoring train

Other model parameters which are needed for a section of a route are the rail roughness as a spectrum or as a single value $L_{\lambda,CA}$. These rail roughness values can also be determined using the indirect measurement method. To do this, the vertical axle bearing accelerations are measured on a test bogie. By adapting equation (7), the effective total roughness during the journey can be determined from the acceleration values [32]. The wheel roughness values of the test axles should be as low as possible, so that even low rail roughness values can be recorded correctly. The roughness values are calculated at all four axle bearings for track sections with a length of 1.8 m. These individual sections are averaged in terms of energy over a range of ten metres, also the roughness level is then determined from these sections.

Figure 15 shows the indirectly measured rail roughness values between the Sissach and Liestal stations on the Basel-Olten route. Marked differences in rail roughness are evident for this section of the route. In addition, the roughness levels of the 10-metre track sections are indicated for one section. On the basis of the wheel roughness values of the test axles, the roughness level does not fall below 4 dB(A). It is to be assumed that in such cases the actual rail roughness is even lower.

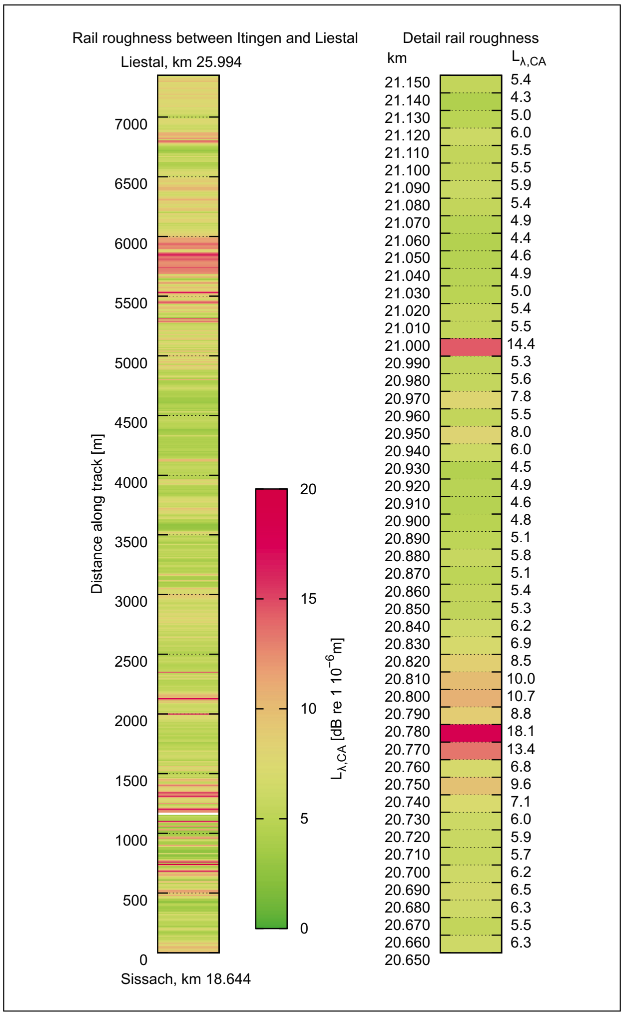

Figure 15. Results of indirect measurement of rail roughness using a monitoring train between Itingen and Liestal and indication of the calculated roughness level $L_{\lambda,CA}$.

4.5. Traction noise

The key emission values of traction unit and set noise can be determined using pass-by and standstill measurements. It must be ensured that where possible each set can be operated and measured separately. Also, all relevant operating states, e.g. fan speed, diesel engine speed and traction power should be recorded. For model integration, the sound pressure levels must be converted back into sound power levels and assigned to the corresponding source height. In the case of pass-by measurements, it must also be ensured that the rolling noise components are negligible, as far as possible.

Measurements using a microphone array may also provide useful information on source distribution and source power.

4.6. Use of acceptance values

The classification and integration of a new vehicle into the emission model is possible using acceptance values, provided all relevant individual parameters have been

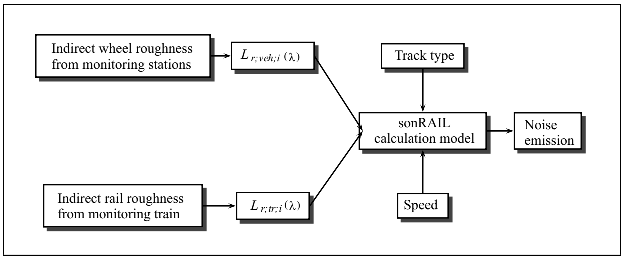

Figure 16. Calculation of emission levels using the indirectly measured wheel and rail roughness.

recorded. If only the pass-by noise is recorded as an A-weighted overall sound pressure level, only a very unsatisfactory integration into the model is possible. Separation of rolling noise and secondary noise is not possible and there is no information on the spectral composition of the pass-by level. The vehicle can be assigned to an existing category according to the vehicle construction. However, for this assignment to be made, the rail roughness of the acceptance track has to be known or at least estimated.

With regard to integration of new vehicles into the model, the following individual parameters should be recorded for acceptance measurements:

1. Sound pressure/sound power spectra between 100 and 8000 Hz, separated for individual secondary sources at a standstill and for pass-bys at 80 km/h,
2. Overall sound pressure level for pass-bys,
3. Wheel/rail roughness or effective total roughness of the indirect measurement.

5. Example calculations for the Bern-Thun-Spiez route

Emission calculations using the *sonRAIL* model can be carried out with the indirect measurement methods described in the preceding paragraphs. To do this, the rail roughness on the Bern-Thun-Spiez route was measured using a monitoring train over a length of approximately 32 km. The route was divided into 3133 sections, each ten metres long. For each of these sections, sound power levels were calculated for different vehicle categories as a function of the measured rail roughness. The emission level was calculated for $v = 80$ km/h using the indirect wheel and rail roughness values corresponding to the diagram in Figure 16.

The results are represented in Figure 17 using the distribution of emission levels along the route. In addition, the track superstructure type and the position of points are indicated. According to the measured rail roughness, very high emission levels are calculated on some sections of the route for disc-braked vehicles. The emission values may be very dispersed by analogy with the results of the measurements between Lausanne and Freiburg. Depending on the wheel roughness, higher values were calculated for K-braked vehicles. In the case of grey cast iron-braked

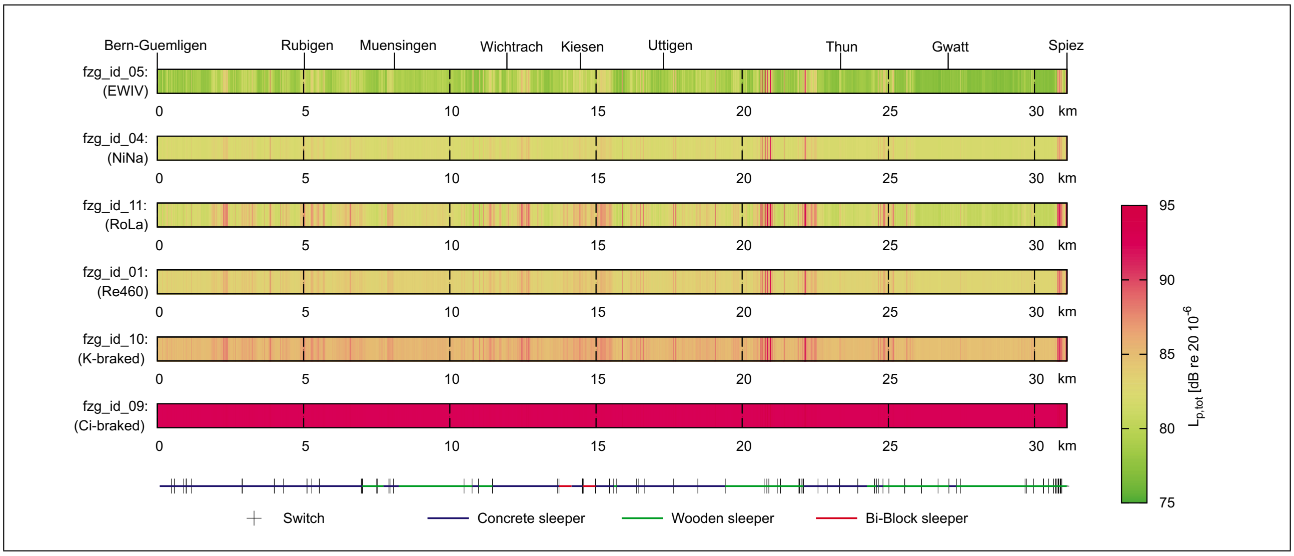

Figure 17. Emission calculations ($L_{p,tot,7.5\,\mathrm{m}}$) for different vehicle categories on the Bern-Thun-Spiez route using indirectly measured rail roughness values from the monitoring train and the results of the indirect roughness measurements at the Wichtrach monitoring station [33]. Results are compared in Table II.

Table II. Measured and calculated pass-by levels ($L_{pA,tot,7.5m}$) at the BAV monitoring station Wichtrach.

	Measured	Calculated
Passenger trains	87.2 dB(A)	87.6 dB(A)
Freight trains	94.6 dB(A)	94.1 dB(A)

vehicles, uniformly high emission levels are calculated regardless of the rail roughness. A comparison of the emission levels on the Federal Office of Transport test site in Wichtrach indicates very good correlation between measurement and calculation. The indirect roughness measurement method in conjunction with the emission model developed is therefore suitable for automatic calculation of emission levels over long sections of routes.

6. Summary

An acoustic emission model for railway noise has been developed on the basis of extensive measurement data. The emission model is a component of the new *sonRAIL* Swiss noise prediction model and allows calculation of sound power levels for five source heights. The model calculation takes into account the essential influencing parameters for noise generation: vehicle and track superstructure type, wheel and rail roughness, line routing parameters, traction unit and set noise. The calculations in the emissions model can be made using standard values or user-specific data. This gives the possibility of extending the emission model to other applications as required.

Using the monitoring method outlined for recording rail and wheel roughness, it is possible to create an accurate data set as a basis for any application. Rolling noise can be calculated for any vehicle as a function of the actual wheel and rail roughness. Accurate delimitation of K-braked and grey cast iron-braked freight wagons in train sets allows correct representation of the vehicle mix on a section of track.

The emission model which has been developed allows accurate assessment and analysis of noise reduction measures. In the process, not only is an overview of the actual current situation obtained, but predictions of the changes in noise as a result of changing general conditions are also possible.

Acknowledgement

The investigations presented were carried out within the framework of the development of the new Swiss *sonRAIL* rail noise model and were financed by the Swiss Federal Office for the Environment.

References

[1] Richtlinie 2002/49/EG des Europäischen Parlaments und des Rates vom 25. Juni 2002 über die Bewertung und Bekämpfung von Umgebungslärm.

[2] K. Ingold: Lärmbelastung in der Schweiz. Ergebnisse des nationalen Lärmmonitorings SonBase. Downloadable from: http://www.umwelt-schweiz.ch/uz-0907-d, 2009.

[3] Bundesamt für Raumentwicklung: Perspektiven des schweizerischen Güterverkehrs bis 2030. Hypothesen und Szenarien. Downloadable from: http://www.are.admin.ch/themen/verkehr, 2004.

[4] J. Oertli: The STAIRRS project, work package 1: a cost-effectiveness analysis of railway noise reduction on a European scale. Journal of Sound and Vibration **267** (2003) 431–437.

[5] H. J. A. van Leeuwen: Railway noise prediction models: A comparison. Journal of Sound and Vibration **231** (2000) 975–987.

[6] BAFU - Bundesamt für Umwelt: *sonRAIL* Projektdokumentation. ISBN 9-783-940727-18-3, IFV Bahntechnik, Berlin, 2010.

[7] F. Krüger: Schall- und Erschütterungsschutz im Schienenverkehr. 2. Auflage. Expert Verlag, 2006.

[8] V. V. Krylov: Noise and vibration from high-speed trains. Thomas Telford Limited, London, 2001.

[9] J. M. Wunderli, K. Eggenschwiler: Überprüfung der aktuellen Version des Schweizerischen Berechnungsmodells für Eisenbahnlärm *SEMIBEL*. Untersuchungsbericht, EMPA, 516.2046, 2000.

[10] M. Hecht, D. Salz: Überprüfung der aktuellen Version des Scheizerischen Berechnungsmodells für Eisenbahnlärm *SEMIBEL*. Teil 2: Emissionsmodell. TU Berlin, 11/01, 2001.

[11] BAV - Bundesamt für Verkehr: Monitoring Eisenbahnlärm: Jahresbericht 2007. http://www.bav.admin.ch, 2007.

[12] STAIRRS project: Classification of rolling stock and track, 2nd draft. 2000.

[13] M. Wirnsberger, M. G. Dittrich: The METARAIL Project. Final report. Project No. RA-97-SC.1080, METARAIL Consortium, 1999.

[14] M. G. Dittrich: The IMAGINE source model for railway noise prediction. Acta Acustica united with Acustica **93** (1997) 185–200.

[15] F. G. De Beer, M. H. A. Janssens, M. G. Dittrich: STAIRRS Level 2 Measurement Methods: Indirect roughness and transfer function. METARAIL report D3b TNO-RPT-020079, TNO, 7, 2002.

[16] D. J. Thompson: The influence of the contact zone on the excitation of wheel/rail noise. Journal of Sound and Vibration **267** (2003) 523–535.

[17] R. A. J. Ford, D. J. Thompson: Simplified contact filters in wheel/rail noise prediction. Journal of Sound and Vibration **293** (2006) 807–818.

[18] Arbeitsgruppe Schienenverkehrslärm der Europäischen Kommission: Positionspapier über die europäischen Strategien und Prioritäten zur Bekämpfung des Schienenverkehrslärms. Downloadable from: http://ec.europa.eu/environment/noise/pdf/sum_railway_noise_de.pdf, 2003.

[19] M. Hecht: Einfluss von Rad- und Schienenrauheiten auf das Rollgeräusch. Messung und Berechnung. ZEVrail Glasers Annalen **132** (2008) 276–290.

[20] A. Rohrbeck, T. Thron: sonRAIL. Die Erweiterung des schweizerischen Lärmmodells für den Schienenverkehr. ZEVrail Gl. Ann. **132** (2008) 95–105.

[21] D. Sehu: *sonRAIL* : ein neues Eisenbahnlärmberechnungsmodell für die Schweiz. RAIL-n.o.i.s.e 2007: Geräuschemission und Lärmminderung, 2007.

[22] A. A. von Lier: The measurement, analysis and presentation of wheel and rail roughness. AEAT report, 1997.

[23] C. Talotte: Railway source models for integration in the new european noise prediction method proposed in Harmonoise. Journal of Sound and Vibration **293** (2006) 975–985.

[24] M. G. Dittrich, X. Zhang: The Harmonoise/IMAGINE model for traction noise of powered railway vehicles. Journal of Sound and Vibration **293** (2006) 986–994.

[25] R. Nota: Hamonoise WP3 engineering method for road traffic and railway noise after validation and fine-tuning. Harmonoise report HAR32TR-040922-DGMR10, DGMR, 2004.

[26] C. Talotte: Hamonoise WP1.2 rail sources. Railway source model and user manual of the database (D13p1). Harmonoise report HAR12TR-040112-SNCF10, SNCF, 2004.

[27] M. G. Dittrich: Work package 6: IMAGINE railway noise source model, default source data and measurement protocol. imagine, TNO, 2005.

[28] EN ISO 3095: Railway application - acoustic - measurement of noise emitted by railbound vehicles. 2005.

[29] prEN 15610: Railway application - noise emission - rail roughness measurement related to rolling noise generation. 2009.

[30] DIN EN 15461: Bahnanwendungen - Schallemission - Charakterisierung der dynamischen Eigenschaften von Gleisabschnitten für Vorbeifahrtgeräuschmessungen. 2008.

[31] M. H. A. Janssens, M. G. Dittrich: Railway noise measurement method for pass-by noise, total effective roughness, transfer functions and track spatial decay. Journal of Sound and Vibration **293** (2006) 1007–1028.

[32] C. Czolbe, D. D. Bella: Assessment of the rail roughness on the Swiss network via indirect measuring method. Euronoise, 2009.

[33] BAV - Bundesamt für Verkehr: Monitoring Eisenbahnlärm: Jahresbericht 2008. http://www.bav.admin.ch, 2008.