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Railway noise measurement method for pass-by noise, total effective roughness, transfer functions and track spatial decay

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Abstract

In recent years, considerable effort has been spent at a European level to establish comprehensive methods for the experimental assessment of rolling noise emission of rail-bound vehicles and tracks. This work was concentrated in the European METARAIL and STAIRRS projects. The objective of these was to improve the accuracy and the reproducibility of pass-by noise measurements compared to the standards that were current at that time. A further aim was to develop experimental methods separately to identify the contributions to rolling noise of the vehicles and the tracks.

In these projects, measurement methods were developed that could determine the combined wheel/rail roughness and the 'transfer functions' for the vehicle and the track, that is, the separate noise contributions per unit roughness. The roughness and transfer function spectra provide a powerful basis by which vehicles and tracks can be characterized by measurement, to a high extent, independent of the running speed and site conditions. Such a description of the track and rolling stock allows the prediction of rolling noise spectra for different combinations of vehicles and track from those at which the characteristics have been measured. The measurement effort is limited; only straightforward one-third octave band measurements of pass-by sound pressure and vertical railhead vibration are needed.

This paper describes the method, giving the derivation of the calculation by which the roughness levels, transfer function spectra levels and the vibration decay rates in the track are determined from the measured quantities. Typical results are shown.

Among other applications, the method allows fast assessment of wheel roughness for whole vehicles or trains, speed-independent assessment of the effectiveness of track and vehicle noise control measures and the separation of rolling noise from noise due to other sources.

1. Introduction

Experience has shown that measurements of train pass-by noise using single microphones have not been able to provide unambiguous assessments of noise control measures. Different noise reductions have been found at different sites and at different train speeds. In recent years, therefore, new measurement methods for

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railway noise have been developed that enable the characterization of noise from railway vehicles and tracks in more detailed terms.

The first objective of these methods is to enable the separation of the contributions of vehicle noise and track noise. This allows a clearer test and quantification of the effect of noise control measures.

A second objective of such techniques is to provide measured data to enable the rolling noise emission of any vehicle on any track to be determined. This needs appropriate vehicle data from measurements which can be 'transferred' from one track site to another, as well as track data that is valid for any vehicle. In other words, the aim is to measure suitable descriptors for Vehicle X measured on Track A, and for Vehicle Y on Track B, that make it possible to predict the sound level of vehicle X on track B and Vehicle Y on Track A.

This paper describes a method that fulfils this function. Some elements of the method have been presented in Refs. [1–3]. Here a complete description is given, restating some of the previous material where necessary with updated material and validation results. First, based on rolling noise theory, a set of functions is defined that, in principle, fulfil the requirement (Section 2). Secondly, measurement approaches are described that can be used to acquire data in that form (Sections 3–5). Results of validation tests are given to illustrate the performance of the approach (Section 6). Finally, conclusions on the efficiency of the method and recommendations for possible improvements are given (Section 7).

The approach presented in this paper forms an important element for the new European statutory calculation scheme for railway noise [4–6]. An application example of the method in the form of the European statutory scheme is not the objective of this paper, for this the reader is directed to Ref. [7].

2. Quantities for rail and track characterization

2.1. Different levels of detail

In recent decades, the understanding of wheel–rail rolling noise has improved considerably. Validated theoretical models such as the 'TWINS' model [8–10] have provided insight into the main influence of parameters and their interaction. It is therefore known that the pass-by level of a particular vehicle is not determined uniquely by the vehicle itself, but that track parameters and especially 'rail roughness' have a strong influence. Conversely, the sound radiated by a track is influenced by the vehicle.

In order to address these issues, the separation of vehicle/track pass-by noise and their mutual influence can be pursued to various 'levels', see Table 1.

At 'level 0' no separation is available. The measurements that satisfy this level of analysis would be pass-by sound pressure levels measured with a single microphone. This data might be post-processed to give an estimate of the sound power level of the source. Such measurements are commonly obtained and can serve a number of purposes. However they cannot provide the data to satisfy the current objectives.

Table 1
Overview several levels of railway noise characterization

	Obtained quantities			Applications and notes
	Total	Vehicle	Track	
Level 0 (no separation)	$L_{p\mathrm{tot}}$			Overall levels, large spread
Level 1 (sound separation)	$L_{p\mathrm{tot}}$	$L_{p\mathrm{veh}}$	$L_{p\mathrm{tr}}$	For assessing track or vehicle noise control measures
Level 2 (sound and roughness separation)	$L_{p\mathrm{tot}}$	$L_{r\mathrm{veh}}$, $L_{H\mathrm{reh}}$, $L_{p\mathrm{veh}}$	$L_{r\mathrm{tr}}$, $L_{H\mathrm{tr}}$, $L_{p\mathrm{tr}}$	For independent characterization of tracks and vehicle
Level 3 (sound roughness and dynamics separation)	$L_{p\mathrm{tot}}$	$L_{r\mathrm{veh}}$, $L_{H\mathrm{reh}}$, $L_{p\mathrm{veh}}$, mobilities and others	$L_{r\mathrm{tr}}$, $L_{H\mathrm{tr}}$, $L_{p\mathrm{tr}}$, mobilities and others	Partly using calculation, when vehicle not available

At 'level 1' pass-by noise is separated into the part radiated by the vehicle and the part radiated by the track. Several such methods have been presented, such as microphone array methods [11–13] or other techniques [14,15]. Within their range of validity, these methods provide the possibility to separate noise radiated by the vehicle and that from the track. This meets the first objective of Section 1. The descriptors at this level are: total pass-by sound pressure level, and sound pressure level of the vehicle and sound pressure level of the track.

However, the second objective in Section 1, is not satisfied. For example, the sound radiated by a vehicle on a particular track does not uniquely characterize that vehicle, since the track roughness has a direct influence. Therefore, a further level of detail, 'level 2', is defined. A method at this level, aims not only to separate the total sound level during a train pass-by into a vehicle part and a track part, but also to provide the wheel and track roughnesses. The quantities to be measured now are: total pass-by sound pressure level, and sound pressure level of the vehicle, sound pressure level of the track, wheel and track roughness spectra (as a function of wavelength).

Strictly speaking, the track-side sound pressure level is influenced by local sound propagation conditions. This can be obviated by taking measurements close to the track (e.g. 7.5 m) and prescribing some minimum conditions with which the measurement site must comply [1,6].

Considering that the sound pressure level of a vehicle will vary from track to track due to roughness level variation, it is now possible to derive the *ratio* of sound pressure to roughness amplitudes. It can be anticipated, based on TWINS theory, that this ratio is, to a good approximation, invariant from site to site. This then fulfils the second objective from Section 1. The next section discusses how these data may conveniently be expressed.

Finally, besides the vehicle and track roughnesses, it is also known from rolling noise theory, that the dynamics of vehicle and track can also influence one another significantly. This could be expressed at a 'level 3' of detail. A measurement method at this level of detail must, in addition to the noise and roughness levels, provide data on wheel, track and contact spring dynamics [8]. However, for the range of common track and wheel types it can be expected that the influence of different dynamic characteristics can be neglected. Only in cases that involve very small wheels, resilient wheels or exotic rail types, is a significant effect on the noise expressed as a dB level to be expected. Therefore, a measurement approach at this level of detail is not pursued here. The remainder of the paper is concerned with 'level 2' characterization.

2.2. Choice of quantities for level 2 measurement methods

In order to handle data of pass-by measurements at the level 2 detail, some conventions and definitions are needed. Fig. 1 presents five quantities that provide a simple breakdown of pass-by noise into quantities determined by the wheel and the track. Wheel roughness, rail roughness and train speed characterize the excitation of rolling noise at the wheel–rail contact. The ratios of the resulting trackside wheel and track noise components to the roughness excitation are expressed as transfer functions.

The transfer function captures every aspect of sound transmission of the vehicle (or track) implicitly: the wheel vibration response to the excitation, its radiation, and the sound transmission to the trackside.

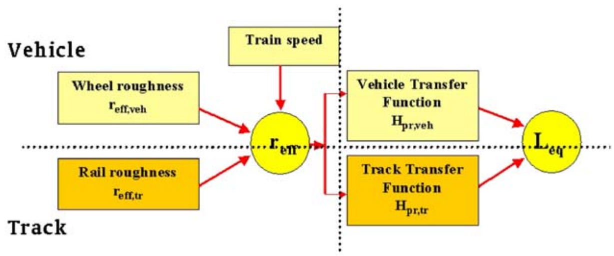

Fig. 1. Measurement quantities for rolling noise, separated into excitation and transfer functions and vehicle and track components. The transfer functions are normalized to the number of axles per unit length and the roughness function is 'filtered' by the contact.

If present, the transfer function also includes the effects of noise control measures such as wheel dampers, wheel type or local shielding. The track transfer function similarly encompasses the effects of track components.

An important property of each transfer function is that they can be assumed to depend only on the respective track or vehicle design, and are independent of the train speed, the roughness levels, and of factors that influence the other transfer function.

2.3. Conventions for wheel and rail roughness

The wheel and rail roughness amplitude levels, $L_{r,w}(\lambda)$ and $L_{r,r}(\lambda)$, are expressed as one–third octave spectra with respect to wavelength λ. The dB reference is 1 μm rms amplitude. The one-third octave band centre values are taken to be in the series 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10 cm and so on.

In the current method, the so-called *effective* roughness is used. This is the roughness spectrum as if the total contact patch was represented by a single point; which means that the effective roughness already includes the averaging and 'filtering' effects of the wheel/rail contact patch. The 'filter' expresses the way in which wavelengths of roughness shorter than the length of the contact patch (in the direction of travel and perpendicular to it) are averaged and thus reduced in effect.

The *combined roughness* of wheel and rail follows from

$$L_{r,\mathrm{tot}}(\lambda) = L_{r,w}(\lambda) \oplus L_{r,r}(\lambda) = 10\log_{10}\left\{10^{(L_{r,w}(\lambda)/10)} + 10^{(L_{r,r}(\lambda)/10)}\right\}, \tag{1}$$

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

This definition of the roughness spectrum differs a little from roughness data that is obtained using a sharply pointed sensor [16,17]. The result using such a sensor does not account for the contact filter effect. Nevertheless, using an appropriate contact filter function $\mathrm{CF}(\lambda)$ [18,19], this 'direct' roughness data can be converted into the effective roughness. The effective rail roughness $L_{r,r}(\lambda)$ relates to the rail roughness measured using direct surface scanning $L_{r,r,\mathrm{dir}}(\lambda)$ as

$$L_{r,r}(\lambda) = L_{r,r,\mathrm{dir}}(\lambda) + \mathrm{CF}(\lambda). \tag{2}$$

A similar expression holds for wheel roughness. The contact filter $\mathrm{CF}(\lambda)$ depends somewhat on the wheel load, the wheel diameter, the wheel profile and the rail profile. Fig. 2 shows the contact filter CF for various wheel diameters and wheel loads.

2.4. Train speed and frequency–wavelength conversion

As the train moves, the wheel and rail roughness passes through the wheel–rail contact area. Roughness of wavelength λ (m) excites the wheel and rail at a frequency f (Hz), depending on the train velocity V (m/s)

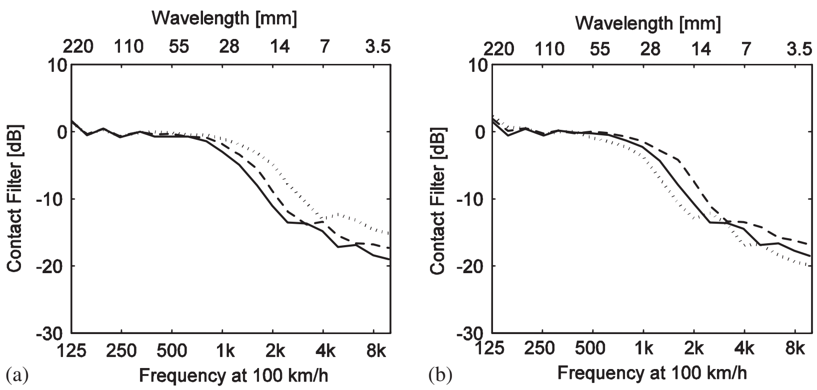

Fig. 2. Average contact filter effect calculated using numerical model for 100 km/h. Left, for 50 kN wheel load and various diameters: ——, 920 mm; – – –, 680 mm; · · · · · ·, 360 mm. Right, for 920 mm diameter and various wheel loads: ——, 50 kN; – – –, 25 kN; · · · · · ·, 100 kN, from Ref. [19].

according to

$$\lambda(V,f) = \frac{V}{f} \quad \text{and} \quad f(V,\lambda) = \frac{V}{\lambda}. \tag{3}$$

So, if the roughness spectrum is available as a function of wavelength $L_r(\lambda)$ a spectrum as a function of frequency $L_r(f)$ can be derived by evaluating $L_r(\lambda)$ at the wavelength corresponding to the frequency f:

$$L_r(f) = L_r(\lambda)|_{\lambda=\lambda(V,f)} \equiv L_r(\lambda(V,f)). \tag{4}$$

Similarly, the conversion from a frequency spectrum to a wavelength spectrum follows from

$$L_r(\lambda) = L_r(f)|_{f=f(V,f)} \equiv L_r(f(V,\lambda)). \tag{5}$$

A linear interpolation of the spectra on decibel scales is implicitly assumed in Eqs. (4) and (5) in order to produce spectra at the preferred one-third octave bands of frequency or wavelength.

2.5. Transfer functions

The ratio of radiated noise and roughness for both vehicle and track are expressed as transfer functions $L_{H,\mathrm{veh}}$ and $L_{H,\mathrm{tr}}$,

$$L_{H,\mathrm{tr}}(f_{\mathrm{to}}) \equiv L_{p,\mathrm{tr}}(V,f_{\mathrm{to}}) - 10\log_{10}\left(\frac{N_{\mathrm{axle}}}{L_{\mathrm{wagon}}}\right) - L_{r,\mathrm{tot}}(\lambda(V,f_{\mathrm{to}})), \tag{6}$$

$$L_{H,\mathrm{veh}}(f_{\mathrm{to}}) \equiv L_{p,\mathrm{veh}}(V,f_{\mathrm{to}}) - 10\log_{10}\left(\frac{N_{\mathrm{axle}}}{L_{\mathrm{wagon}}}\right) - L_{r,\mathrm{tot}}(\lambda(V,f_{\mathrm{to}})), \tag{7}$$

where f_{to} is the one-third octave band centre frequency, $L_{p,\mathrm{tr}}(V,f_{\mathrm{to}})$ is the measured equivalent continuous sound pressure level from the track at pass-by speed V taken over the time interval for the vehicle to pass the measurement location 'from buffer to buffer', $L_{p,\mathrm{veh}}(V,f_{\mathrm{to}})$ is the equivalent continuous sound pressure level for the vehicle, N_{axle} is the number of axles per wagon and L_{wagon} is the wagon length.

Since the roughness is a function of a single wheel–rail contact but the sound levels depend on the spacing of the axles, the vehicle and track transfer functions must be normalized for the axle density $N_{\mathrm{axle}}/L_{\mathrm{wagon}}$.

The transfer function may be described as the sound pressure level at the trackside corresponding to one axle per metre length of the vehicle, due to a combined roughness amplitude of 1 μm.

Although not directly obvious from Eqs. (6) and (7), rolling noise theory shows that the effects of rolling on the frequency content of the spectrum are small enough for the transfer functions to be assumed not to depend on train speed. The change in sound pressure level with the train speed is caused by the frequency shift of the roughness spectrum only. This holds as long as linear theory applies (not where wheel flats or severe rail surface defects exist), and no sound sources other than rolling noise are significant in the measured sound pressure signal.

2.6. Trackside total sound pressure level

Using the definitions of the previous sections, the trackside vehicle sound pressure can be reconstructed using:

$$L_{p,\mathrm{veh}}(V,f_{\mathrm{to}}) = L_{H,\mathrm{veh}}(f_{\mathrm{to}}) + 10\log_{10}\left(\frac{N_{\mathrm{axle}}}{L_{\mathrm{wagon}}}\right) + L_{r,\mathrm{tot}}(\lambda(V,f_{\mathrm{to}})) \tag{8}$$

and a similar expression exists for the track noise $L_{p,\mathrm{tr}}(f)$. The total sound level due to rolling noise is the energy sum of vehicle and track noise:

$$L_{p,\mathrm{tot}}(V,f) = L_{p,\mathrm{veh}}(V,f) \oplus L_{p,\mathrm{tr}}(V,f). \tag{9}$$

2.7. How the quantities are used

This section will illustrate the way in which the defined quantities can be used.

Suppose the measurement of a vehicle I at Site A yields the transfer functions according to Eqs. (6) and (7), denoted in short for the vehicle: HV_I and for the track HT_A, and the roughness spectra RV_I and RT_A. The sound radiated by the vehicle $PV_{I\text{ on }A}$ thus is (corrections for axle density are implicitly assumed)

$$PV_{I\text{ on }A} = HV_I + (RV_I \oplus RT_A). \tag{10}$$

The sound radiated by the track is

$$PT_{I\text{ on }A} = HT_I + (RV_I \oplus RT_A). \tag{11}$$

This illustrates that the first objective from Section 1, i.e. of separation of vehicle and track noise. Further, if a similar set of data is available from a vehicle *II* measured at Site *B*, not only can the sound of the vehicle at Site *B* be estimated using

$$PV_{II\text{ on }B} = HV_{II} + (RV_{II} \oplus RT_B). \tag{12}$$

but also the sound it would produce at Site A

$$PV_{II\text{ on }A} = HV_{II} + (RV_{II} \oplus RT_A). \tag{13}$$

The track noise component is given by

$$PT_{II\text{ on }A} = HT_I + (RV_{II} \oplus RT_A) \tag{14}$$

and the total pass-by noise is

$$\begin{aligned} P_{\text{total }II\text{ on }A} &= PT_{II\text{ on }A} \oplus PV_{II\text{ on }A} \\ &= \{HT_I + (RV_{II} \oplus RT_A)\} \oplus \{HV_{II} + (RV_{II} \oplus RT_A)\}. \end{aligned} \tag{15}$$

This illustrates that the transfer functions and roughnesses form a set of 'building blocks' to derive rolling noise of any vehicle on any track. Thus the second objective of Section 1 is met.

The following sections present measurement techniques to provide the level 2 parameters that can be made during on running service trains. However, any set of measurements, however achieved, that yields the quantities can be used to undertake the purposes of the level 2 data that have been outlined. The object here is measurements that can be carried out in a convenient and cost-effective way.

3. Measurement methods for roughness spectra

3.1. Determination of rail roughness

The effective roughness of the rail at the measurement site can be measured using commercially available rail roughness instruments which use a needle-shaped sensor [16,17]. This roughness should be processed according to the instruction valid for the particular instrument. Measurement of track roughness is considered state-of-the-art practice. In order to produce the effective roughness as defined here, a contact filter should be applied to data measured in this way according to Eq. (2).

3.2. Determination of wheel roughness

Individual wheel roughness measurements can also be made using a contacting probe device. However, this is time consuming. A great practical advantage would be gained by being able to obtain wheel roughness spectra of trains in service passing a particular measurement site. Therefore, an alternative approach is proposed. The combined roughness of wheel and rail can be determined from track vibration measurements during train pass-bys [1,20]. Then, the wheel roughness spectrum is determined as

$$L_{r,w}(\lambda) = 10\log_{10}(10^{L_{r,\text{comb}}(\lambda)/10} - 10^{L_{r,r}(\lambda)/10}) \equiv L_{r,\text{comb}}(\lambda) \ominus L_{r,r}(\lambda), \tag{16}$$

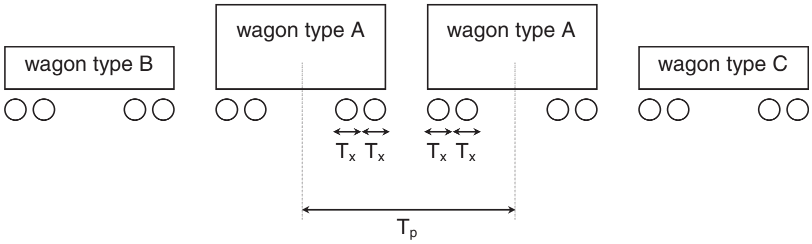

Fig. 3. To measure vehicle type A, at least two wagons are required.

where the $\ominus$ operator is used to represent an energy subtraction. This approach allows the derivation of the vehicle roughness spectra of any vehicle passing the measurement site. To the knowledge of the authors, no other method exists to acquire roughness spectra of service vehicles passing a measurement site. Because of the energy subtraction involved, it is only practically possible to obtain a stable measurement of the wheel roughness if the rail roughness level is, by comparison, low.

3.3. Determination of combined roughness

The combined effective roughness of wheel and the rail is derived directly from the measurement of vertical rail vibrations. The one-third octave band levels $L_{a,\mathrm{meas}}(f_{\mathrm{to}})$ of the average acceleration over the wheel passage interval T_x is determined, see Fig. 3. This interval is taken as the time for the wheel to travel a short distance e.g. 1.8 m; the moment the wheel passes the accelerometer is taken as the centre of this interval. The combined roughness follows from

$$L_{r,\mathrm{tot}}(f_{\mathrm{to}}) = L_{a,\mathrm{meas}}(f_{\mathrm{to}}) - A_1(f_{\mathrm{to}}) - A_2(f_{\mathrm{to}}) - A_4(f_{\mathrm{to}}) - 40\log_{10}(2\pi f_{\mathrm{to}}), \tag{17}$$

where $L_{r,\mathrm{tot}}(f_{\mathrm{to}})$ is the one-third octave band level of combined effective roughness of wheel and rail and $L_{a,\mathrm{meas}}(f_{\mathrm{to}})$ is the one-third octave band level of measured *equivalent* vertical rail acceleration, averaged over the wheel passage time interval T_x. $A_1(f_{\mathrm{to}})$ is the level difference between the average vibration at the measurement position (for example, underneath the rail) and the rail head,

$$A_1(f_{\mathrm{to}}) = L_{a,\mathrm{meas}}(f_{\mathrm{to}}) - L_{a,\mathrm{head}}(f_{\mathrm{to}}). \tag{18}$$

$A_2(f_{\mathrm{to}})$ is the level difference between the vibration displacement at the contact point on the rail head and the combined effective roughness $L_{r,\mathrm{tot}}(f_{\mathrm{to}})$,

$$A_2(f_{\mathrm{to}}) = L_{x,\mathrm{contact}}(f_{\mathrm{to}}) - L_{r,\mathrm{tot}}(f_{\mathrm{to}}). \tag{19}$$

$A_4(f_{\mathrm{to}})$ is the level difference between the vibration at the contact point and the average vibration over the wheel passage interval T_x[1]

$$A_4(f_{\mathrm{to}}) = L_{a,\mathrm{head}}(f_{\mathrm{to}}) - L_{a,\mathrm{contact}}(f_{\mathrm{to}}). \tag{20}$$

The term $40\log_{10}(2\pi f_{\mathrm{to}})$ converts from acceleration $L_{a,\mathrm{contact}}(f_{\mathrm{to}})$ to displacement $L_{x,\mathrm{contact}}(f_{\mathrm{to}})$.

3.3.1. Conversion spectrum A_1

The accelerometer will be not be located on the rail head, but at a different part of the rail cross-section. $A_1(f_{\mathrm{to}})$ converts the measured acceleration $L_{a,\mathrm{meas}}(f_{\mathrm{to}})$ to the vertical acceleration of the rail head $L_{a,\mathrm{head}}(f_{\mathrm{to}})$, accounting for the cross-sectional deformation of the rail. In Ref. [3] it is shown, that $A_1(f_{\mathrm{to}}) \approx 0$ up to 4 kHz for an accelerometer underneath the centre of the rail foot in the vertical direction.

3.3.2. Conversion spectrum A_2

The level difference $A_2(f_{\mathrm{to}})$ between the vibration displacement at the contact point $L_{x,\mathrm{contact}}(f_{\mathrm{to}})$ on the rail head and the combined effective roughness $L_{r,\mathrm{comb}}(f_{\mathrm{to}})$, which describes to which extent roughness induces rail

[1] A_3 is not used, but numbering of conversion spectra is maintained for comparison with existing literature.

Table 2
Spectra $A_2(f_{to})$ for three categories of rail pad stiffness (from Ref. [19])

Frequency (Hz)	Soft pad	Medium pad	Stiff pad
63	1.0	−3.0	−3.0
80	4.1	2.3	2.3
100	2.7	2.6	2.6
125	0.9	0.8	0.8
160	0.1	0.0	0.0
200	0.0	0.0	0.0
250	−0.6	0.0	0.2
315	−1.2	−2.6	−0.1
400	−1.3	−3.9	−2.8
500	−0.9	−4.8	−6.5
630	−0.9	−3.2	−8.1
800	−1.6	−2.6	−6.9
1000	−2.7	−4.3	−5.0
1250	−5.6	−6.2	−4.4
1600	−8.0	−7.5	−6.4
2000	−9.5	−8.8	−8.4
2500	−10.0	−9.8	−9.5
3150	−11.3	−11.2	−11.1
4000	−13.7	−13.6	−13.6
5000	−14.9	−14.8	−14.8

Table 3
Ranges of pad stiffness applying to different categories of pads used in defining standard spectra for A_2 [19]

	Soft pad	Medium pad	Stiff pad
Bibloc sleeper	$\leqslant$400 MN/m	400–800 MN/m	$\geqslant$800 MN/m
Monobloc sleepers	$\leqslant$800 MN/m	$\geqslant$800 MN/m	–
Wooden sleepers	All	–	–

vibration, is the result of the wheel rail interaction. As shown in Ref. [19],

$$A_2 = 20\log_{10}\left(\frac{|\alpha_R|}{|\alpha_R + \alpha_W + \alpha_C|}\right), \tag{21}$$

where α_R is the rail point receptance at the contact, α_W is the wheel point receptance at the contact and α_C the receptance of the contact stiffness.

Frequencies where $|\alpha_R| \gg |\alpha_W + \alpha_C|$ give $A_2 \approx 0$ dB. This often occurs in practice between 100 and 1000 Hz. A study [18,19] using the TWINS model, shows that the spectrum A_2 in fact does depend slightly on the track properties. The pad stiffness is shown to be the most influential parameter. The spectrum of A_2 is listed in Table 2 for the 63–5000 Hz one-third octave frequency bands for different ranges of pad stiffness. The ranges of pad stiffnesses are given in Table 3. These values of A_2 are determined to within a variation of ± 3 dB in individual one-third octave bands for a range of conventional wheels. This uncertainty is transferred to the result for the combined roughness. Since this does not lead to greater uncertainties than those found in conventional roughness measurements, it is acceptable. Averaging over more measurements with different train speeds further diminish this distribution since peaks and dips in the frequency spectrum A_2 average out.

3.3.3. Conversion spectrum A_4

The level difference $A_4(f_{to})$ between the vibration at the contact point $L_{a,\mathrm{contact}}(f_{to})$ and the average vibration over the wheel passage interval $L_{a,\mathrm{head}}(f_{to})$ depends on the track decay rate, i.e. the spatial vibration decay D along the track, which is expressed in dB/m [1,3]:

$$A_4(f_{\rm to}) = L_{a,{\rm head}}(f_{\rm to}) - L_{a,{\rm contact}}(f_{\rm to}) = 10\log_{10}\left\{\frac{8.686}{VDT_x}\{1 - {\rm e}^{(-VDT_x/8.686)}\}\right\} \approx \frac{D}{2.75}. \tag{22}$$

3.3.4. Determination of spatial decay

The vibration decay D from Eq. (22) can be derived from hammer impact measurement [21] (usually an unloaded track) or from the pass-by measurements themselves by evaluating the vibration decay around a wheel. This latter approach has the advantage of determining the decay with the presence of the pre-load of the train.

For a pass-by vibration measurement, the rail vibration amplitude is assumed to be described by an exponential function

$$A(z) \approx A(0){\rm e}^{-\beta z}, \tag{23}$$

where z is the position away from the contact point along the rail, $A(z)$ is the vibration amplitude along the rail, $A(0)$ is the instantaneous amplitude at the position of the wheel contact point and β is a decay term. The decay rate D in dB/m can be given as

$$D = 20\log_{10}({\rm e}^{\beta}) = 8.686\beta\,{\rm dB/m}. \tag{24}$$

The decay D is derived from the evaluation of the ratio of the integrated vibration level over a length L_2 versus the integrated vibration over a short length L_1 directly around the wheels. L_2 is taken as a relatively long length, e.g. the whole train pass-by, a group of wagons, or a vehicle length. The corresponding time interval is T_p (Fig. 3). L_1 is taken as 1.8 m, from −0.9 to +0.9 m around each wheel position, corresponding to the time interval T_x in Fig. 3. The wheel position is determined by a wheel-position trigger signal in the measurements.

The integrated squared vibration amplitude over a length L_1 around all N wheels is, using Eq. (23)

$$A^2_{\Sigma L_1} = \sum_{n=1}^{N} A^2_{n,L_1} = \sum_{n=1}^{N}\int_{-L1/2}^{L1/2} (A_n(0){\rm e}^{-\beta z})^2\,{\rm d}z = \frac{1-{\rm e}^{\beta L_1}}{\beta}\sum_{n=1}^{N} A_n^2(0). \tag{25}$$

Similarly, the integrated squared vibration amplitude over a long length L_2 incorporating all N wheels is

$$A^2_{\Sigma L_2} = \sum_{n=1}^{N}\int_{L_2} (A_n(0){\rm e}^{-\beta z})^2\,{\rm d}z = \frac{1-{\rm e}^{-\beta L2}}{\beta}\sum_{n=1}^{N} A_n^2(0) \approx \frac{1}{\beta}\sum_{n=1}^{N} A_n^2(0). \tag{26}$$

The approximation on the right-hand side of Eq. (26) is valid for sufficiently large L_2, e.g. a train length or the length of a (group of) vehicle(s).

The quantities $A^2_{\Sigma L_1}$ and $A^2_{\Sigma L_2}$ can be determined straightforwardly from measured acceleration signals. The transducer time signal is passed through one-third octave band pass filters. Then, for each frequency band, the integrated squared vibration is determined.

Now, using Eqs. (3) and (4), the vibration decay can be determined from the measured ratio R of $A^2_{\Sigma L_1}$ and $A^2_{\Sigma L_2}$ as

$$R(f) = \frac{A^2_{\Sigma L_1}(f)}{A^2_{\Sigma L_2}(f)} = 1 - {\rm e}^{-\beta L_1}. \tag{27}$$

From Eqs. (27) and (24) the vibration decay D is

$$D(f) = -\frac{8.686}{L_1}\log_{10}(1 - R(f)). \tag{28}$$

For low decay rates (about 3 dB/m or less), the contribution of neighbouring wheels to the quantity A^2_{n,L_1} will not be negligible. This can be corrected for in an iterative way. First, the decay is computed as above without considering the contribution from neighbouring wheels. Then, the contribution from the neighbouring wheels is estimated using the resulting decay rate from the first step and Eq. (23). This results in an updated value of A^2_{n,L_1} due to the wheel in the L_1 interval only. This process is repeated a number of times and typically converges within four to five steps.

3.3.5. Precautions for combined roughness determination

A method has been presented for deriving the combined roughness spectrum based on a pass-by (vibration) measurement. Due to the fact that track decay rates can be quite high (over 10 dB/m), sometimes only a section of the wheel circumference is effectively sampled. It is therefore highly recommended to apply accelerometers at more than one measurement section (at distances not a multiple of the wheel circumference) and average over those positions.

Further, the presence of rail joints or rail surface irregularities in the vicinity of the accelerometers should be avoided. On tracks with moderate-to-high decay, a distance of 10 m or more is preferable.

4. Measurement methods for transfer functions

4.1. Combined transfer function measurement

From a single train pass-by, the combined effective roughness can be determined. The combined transfer function is found by subtracting this roughness from the measured sound level,

$$L_{H,\mathrm{tot}} = L_{p,\mathrm{tot}} - 10\log_{10}\left(\frac{N}{L}\right) - L_{r,\mathrm{tot}}. \tag{29}$$

The basic measurement set-up consists of one microphone and one accelerometer, see Fig. 4. The microphone position is 7.5 m from the track centre and 1.2 m above rail head. To avoid interference from accompanying wheel types, at least two vehicles of one type are required (Fig. 3). The equivalent sound pressure level $L_{p,\mathrm{tot}}(f_{\mathrm{to}})$ is measured by taking the average sound pressure level over interval T_p. The vertical rail acceleration is measured underneath the centre of the rail foot. The rail acceleration $L_{a,\mathrm{meas}}(f_{\mathrm{to}})$ should be averaged over T_x to obtain $L_{r,\mathrm{tot}}(V/f_{\mathrm{to}})$.

4.2. Derivation of track and vehicle transfer function using a ‘reference vehicle’

Suppose a vehicle should exist that radiated no sound itself. In that case, the track transfer function equals the measured combined transfer function (Eq. (29)) for a pass-by of that vehicle,

$$L_{H,\mathrm{track}} \equiv L_{H,\mathrm{tot}}|_{\mathrm{ref.vehicle}} = L_{p,\mathrm{tot}} - 10\log_{10}\left(\frac{N}{L}\right) - L_{r,\mathrm{tot}}\Big|_{\mathrm{ref.vehicle}}. \tag{30}$$

Of course, all vehicles will radiate sound, so a useful approximation of such a vehicle is sought. In Refs. [3,7] it is shown that a vehicle with small wheels provides a useful approximation to this ideal vehicle. Some example data of a ‘reference vehicle’ will be presented in Section 6.

Similarly, the vehicle reference function could be determined using a ‘reference track’, a track with very low noise emission. Alternatively, the vehicle transfer function can be derived from the energy difference of the

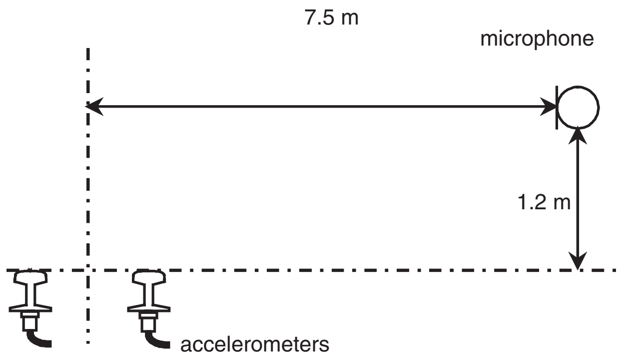

Fig. 4. Location of microphone at track side and accelerometers underneath the rail foot.

track transfer function and the total transfer function of a particular vehicle A,

$$L_{H,\mathrm{veh}} = L_{H,\mathrm{tot}}|_{\mathrm{veh}\,A} \ominus L_{H,\mathrm{tot}}|_{\mathrm{ref.vehicle}}. \tag{31}$$

4.3. Precautions for transfer function determination

The method presented is valid under the following conditions. No sources other than rolling noise should be present (e.g. no aerodynamic effects at high-speed trains, no horns sounding, no train pass-bys on the adjacent tracks). Especially in the lower frequency range (below 100 Hz) and/or lower train speeds (below 40 km/h) care must be taken over traction noise. Braking of the train should be avoided during determination of the transfer functions to avoid braking noise. If the roughness of the two rails of the track differ greatly, the measured transfer function will not be representative, as the noise of the wheel and the rail on one side of the track will be predominant.

5. Measurement recipe

This section gives a short 'recipe' for applying the measurement methods of Sections 3 and 4. Although these methods do involve some post-processing, the actual data acquisition in the field does not involve much additional effort compared with an ordinary pass-by measurement.

In order to derive the transfer functions and roughness spectra of a vehicle and rail, the following steps are taken.

1. Instrument the track according to Fig. 4. In one measurement cross-section, one accelerometer and one microphone are used. Preferably, a trigger device is used to indicate the precise wheel passing times.
2. Measure pass-bys using the above set-up for the desired vehicles and speeds.
3. Measure some pass-bys using a 'reference' vehicle.
4. Measure the track roughness spectrum directly.

This concludes the measurements. The following post-processing is needed.

5. Determine the spatial decay using Eq. (28).
6. Determine combined roughness levels using Eq. (17).
7. Determine wheel roughness level using Eq. (16).
8. Determine combined transfer function using Eq. (29).
9. Determine transfer function of the reference vehicle using Eqs. (29) and (30).
10. Determine vehicle transfer function using Eq. (31).

Steps 5–10 can be performed at various speeds for various pass-bys. If more pass-bys at various train speeds are available it is advisable to average the results.

6. Validation results

6.1. Results at one site

This section presents experimental results from field tests in Caen (France) [20]. This test site consisted of a wooden sleepered track. Three types of vehicles passed over this site: a G50 freight wagon, a Corail passenger coach (both with 930 mm wheel diameter) and the Novatrans container wagon (730 mm wheel diameter), used as a reference vehicle.

In order to validate the proposed measurement methods, the following tests were carried out.

1. Comparison of roughness levels from pass-by data with direct roughness measurements (Section 6.1.1).
2. Comparison of track spatial decay from pass-by data with hammer impact measurements (Section 6.1.2).

3. Comparison of transfer functions extracted from pass-by data, with transfer functions derived in an alternative manner (Section 6.1.3).
4. Comparison of the reference vehicle transfer function with other vehicle transfer functions. The transfer function should be considerably lower than that of other vehicles (Section 6.1.4).
5. Self-consistency test: transfer functions and roughness spectra should not depend on train speed, hence, once determined, the combination of both should reconstruct measured pass-by noise at any pass-by speed (Section 6.1.5).

6.1.1. Roughness measurement

Fig. 5 presents (combined) roughness levels of all three vehicles and the directly measured track roughness. It is found that, in the wavelength range 2–8 cm, the vehicle roughness is predominant. Unfortunately, no direct vehicle roughness measurements of the wheels were available for comparison.

6.1.2. Spatial decay measurement

The track spatial decay is an auxiliary function needed to derive the combined roughness spectra. Fig. 6 presents the spatial decay for the current site calculated from pass-by data, as well as that derived from hammer impact tests. Fig. 6 shows good agreement between these functions. For frequencies in the 800 Hz and higher bands, the decay from pass-by measurements falls largely within the decay range of the two hammer measurements on the left and right rails. In the 200–800 Hz bands, the decay from pass-by data is higher, about 1.5–2 dB. It should be noted that some differences between the pass-by method and hammer method are to be expected, since the pass-by method evaluates the track with the preload of the train present, whereas the hammer method evaluates the track without preload.

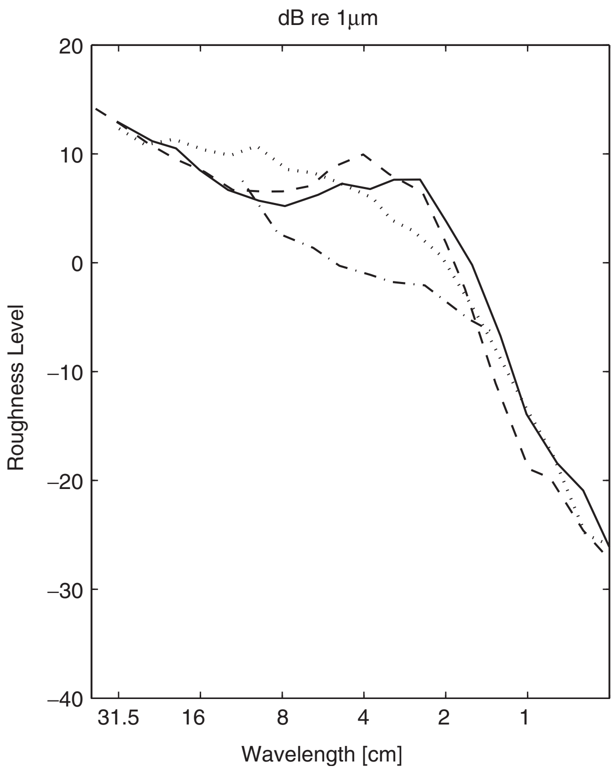

Fig. 5. Combined effective roughness for three wheel types + rail of Site 1 from pass-by measurements and direct measured rail roughness with contact filter: ——, combined wheel + rail roughness G50 Freight from pass-by; - - - - -, Corail wheel + rail from pass-by; · · · · · · · · ·, Novatrans wheel + rail from pass-by; –·–·–, rail roughness from direct scanning.

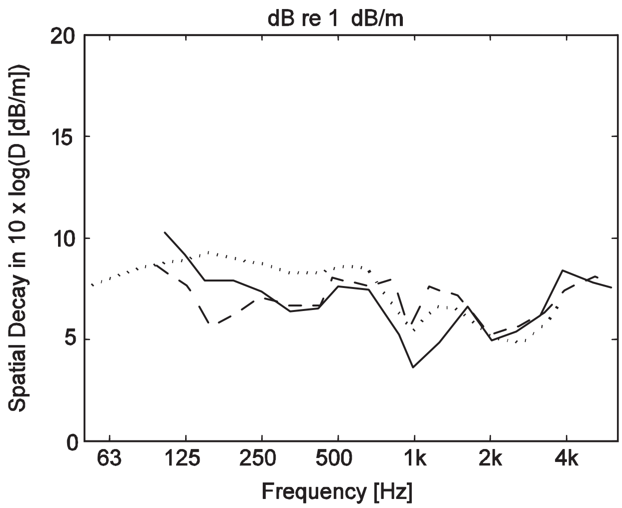

Fig. 6. Vibration decay along track of Site 1 from pass-by measurement and hammer impact (direct) on both rails: ——, rail a; - - - - -, rail b; · · · · · · ·, derived from pass-by measurement.

6.1.3. *Transfer function measurement reference vehicle*

Fig. 7 presents the combined transfer function, measured using pass-by data for the Novatrans vehicle. During the measurement campaign in Caen, the vehicle and track transfer function were also measured directly using artificial excitation of the (static) vehicle and track separately, while recording sound at the trackside position [20]. This yields directly a vehicle transfer function and a track transfer function. The energy sum of these gives the total transfer function. These three curves are also shown in Fig. 7. The figure shows a good agreement between the measured combined transfer function from pass-by data and the directly measured combined transfer function; agreement is within ± 3 dB in each one-third octave band.

The directly measured transfer functions show that, at this particular site, the track transfer function dominates the combined transfer function up to 2 kHz. Only in the 2500 Hz, 3150 Hz and perhaps the 1250 Hz bands does the directly measured vehicle transfer function of the Novatrans vehicle exceed the measured track transfer function. This confirms that the Novatrans vehicle can serve as a reference vehicle for this site.

6.1.4. *Combined transfer function of other vehicles*

Fig. 8 presents the combined transfer function of all three vehicles tested at Caen. In the frequency range up to about 800 Hz, these functions appear very similar. Recalling Fig. 7, this means that in this frequency range, the pass-by sound of all three vehicles is dominated by track radiation.

In the 1000 Hz band and for higher frequencies, the differences are more pronounced (although a bit obscured by the steep slope in this frequency range). The transfer function of the Novatrans vehicle is consistently lower by 3–6 dB. In this range, the vehicle transfer dominates for the Corail and G50 vehicle.

Fig. 9 illustrates the distribution found in a transfer function measurement. The dotted lines present transfer function determination at four different pass-by speeds, with four pass-by's per speed, giving 16 recordings in total. Fig. 9 shows that all samples fall within a band of about 4 dB. The thicker solid line represents the average transfer function. The standard deviation of the distribution varies; it is about 1.5 dB in for the 250 Hz band and higher. A larger standard deviation of about 3 dB is found in the lower frequency bands.

6.1.5. *Self-consistency*

Having roughness spectra and transfer functions available (Figs. 5 and 8) it is possible to reconstruct the pass-by sound pressure at any speed, using Eq. (29). This can be compared with the sound pressure level which is measured at that speed. Fig. 10 presents an example of this reconstruction, for the G50 freight vehicle at three speeds. The reconstruction of the pass-by levels is very reasonable. Differences up to about 3 dB in individual one-third octave bands occur. The difference in reconstructed overall A-weighted level is less than

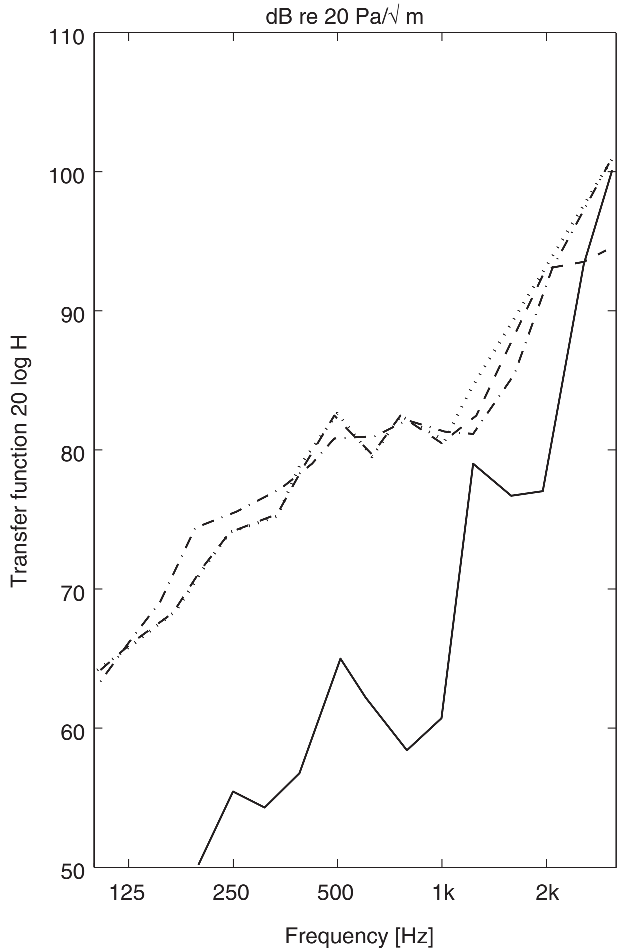

Fig. 7. Four transfer functions: ——, reference (Novatrans) vehicle measured statically; - - - - -, track measured statically; · · · · · · ·, combined vehicle and track measured statically; –·–·–, combined measured during a train pass-by.

1 dB. This exercise has also been carried out for the two other vehicle types and summarized in Table 4. From Fig. 10 and Table 4 it is concluded that the data is self-consistent. The overall *A*-weighted pass-by levels are reconstructed using the roughness spectra, transfer functions and train speed with a minimum difference of 0 dB, a maximum difference of 1.8 dB and a mean difference of 0.6 dB.

6.2. Comparison of results at two different sites

The previous section tested the generation of the roughness spectra at transfer function at a particular site, Site 1. Now this can be compared with data from another site, Site 2, at which the same vehicles have run. This site consisted of a track with monobloc concrete sleepers and UIC60 rail type. Following the second objective from Section 1, it is sought to 'transfer data' from one site to another. Therefore the following tests were carried out:

1. Comparison of vehicle roughness spectra of the same vehicle acquired at two different sites (Section 6.2.1).
2. Comparison of vehicle transfer function of the same vehicle acquired at two different sites (Section 6.2.2).
3. Cross-consistency check. Reconstruction of the pass-by sound at one site by using the vehicle transfer and vehicle roughness from the other site (and vice versa).

These tests were performed using the G50 freight vehicle data.

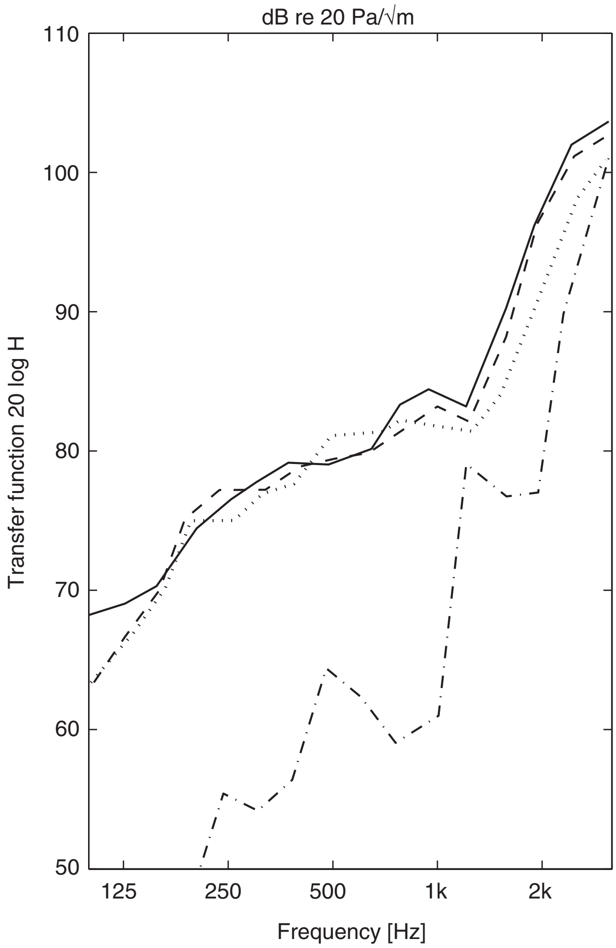

Fig. 8. Combined transfer function for three wagon types + track of Site 1 from pass-by measurement (——, G50; - - - - -, Corail; · · · · · · ·, Novatrans) and direct measured transfer function for reference vehicle (–·–·–).

6.2.1. *Roughness spectra*

Fig. 11 presents the roughness spectra derived from pass-by data of the G50 freight vehicle at both sites (solid and dashed line). Ideally, the same roughness is expected. It is found that, although the general shape of the spectra are similar, considerable differences up to about 4 dB in individual one-third octave bands occur.

These differences are probably not due to a difference in track roughness. The dotted and dash–dotted lines present the directly measured rail roughness spectra at both sites. In the majority of the wavelength range, it is clear that the wheel roughness is dominant. The difference in roughness of the vehicle at the two sites is therefore due to a bias error.

6.2.2. *Combined transfer functions*

Fig. 12 presents the (combined) transfer function of the G50 freight vehicle at both sites. In the frequency range up to about 1000 Hz large difference are found. This is caused by the fact that the track transfer function is dominant in this range, as was shown in Section 6.1. Good agreement is therefore only expected in the frequency range above 1000 Hz. In this frequency range, the transfer functions are indeed close to each other.

The combined transfer function at each site for the Novatrans reference vehicle is also shown. These curves show that, in the frequency range 160–1000 Hz, the transfer functions found for the reference vehicle are very similar to those found for the G50 freight vehicle, indicating the dominance of the track radiation in this range.

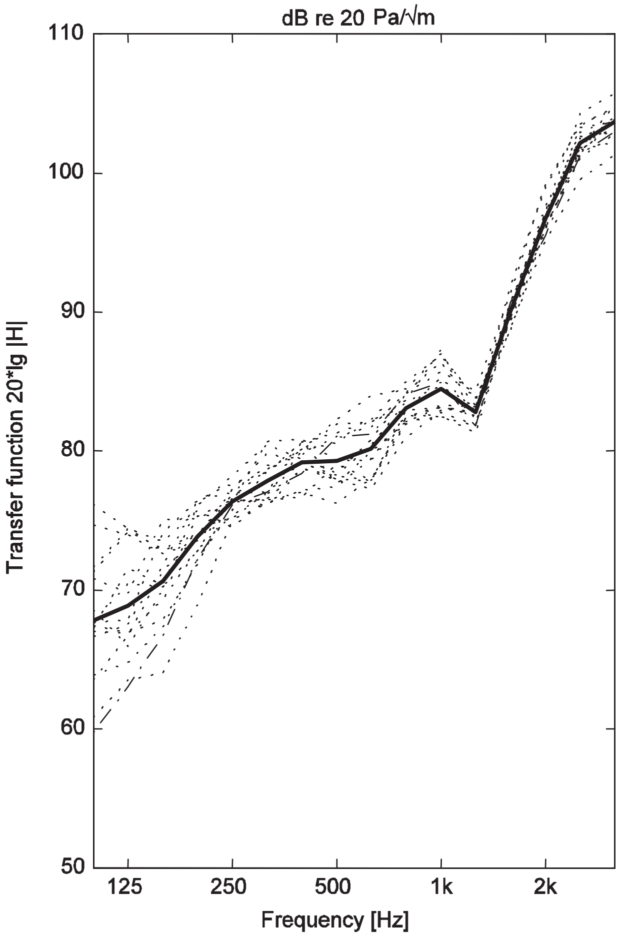

Fig. 9. Average combined transfer function G50 wagon (——) on Site 1 from pass-by measurements and (· · · · · · ·) from individual pass-by at four speeds.

Further, Fig. 12 shows that the *difference* in transfer function of these two vehicle types is found consistently on both tracks. This also illustrates the portability of the transfer functions. Different behaviour of the vehicles is found consistently on either site, irrespective of differences in roughness levels.

6.2.3. Cross-consistency check

A final test performed here, is a cross-consistency test. Since the vehicle transfer function and the vehicle roughness function are supposed to be independent of the test site, it should be possible to reconstruct the pass-by sound pressure spectrum of a vehicle at a particular site, using vehicle data acquired at another site.

From Sections 6.2.1 and 6.2.2 the combined roughness spectra and combined transfer functions at two sites are available. First, these functions are split into track and vehicle roughness, and into track and vehicle transfer functions. Rather than taking energy differences according to Eqs. (16) and (31), it was accomplished here by taking the roughness at $\lambda > 10$ cm and $\lambda < 1.25$ cm (based on Fig. 5) as track roughness and the complementary frequency range as vehicle roughness (based on Fig. 8). The transfer function was split into a track transfer function for frequencies below 1000 Hz and a vehicle transfer function for the 1000 Hz and higher frequency bands.

Fig. 13 presents the measured and reconstructed pass-by levels for the G50 Freight vehicle at 100 km/h at the first site. Some significant differences are found, up to about 4 dB especially in the range 400–1000 Hz. This

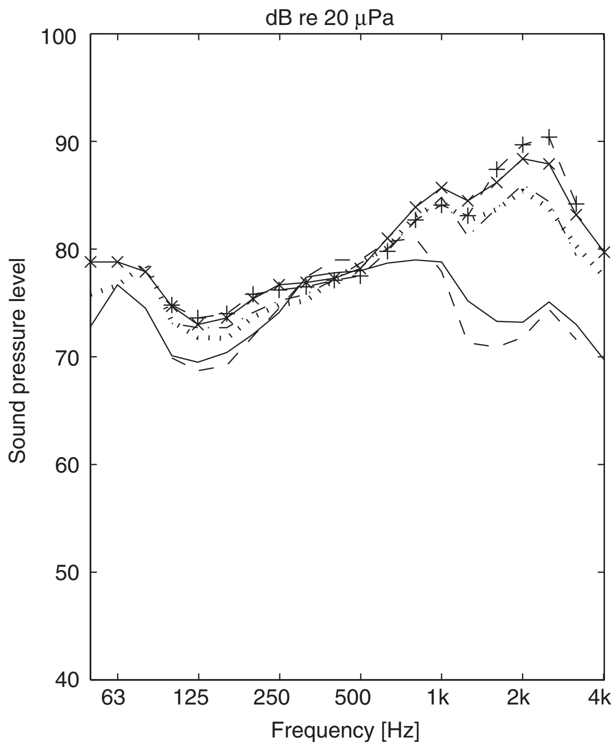

Fig. 10. Measured sound pressure levels at 7.5 m for three speeds and reconstructed levels using roughness and transfer functions. ——, 60 km/h measured, 86.4 dB(A); – · – · –, 60 km/h calculated, 86.4 dB(A); · · · · · · · · ·, 100 km/h measured, 93.2 dB(A); –·–·–, 100 km/h calculated, 93.1 dB(A); × —— ×, 120 km/h measured, 95.7 dB(A); + – – +, 120 km/h calculated, 96.6 dB(A).

Table 4
Self-consistency test for Site 1 at Caen: measured A-weighted pass-by sound pressure levels at 7.5 m in dB and reconstructed levels using roughness spectra, train speed and transfer functions

Speed (km/h)	Corail		G50 Freight		Novatrans	
	Measured	Reconstructed	Measured	Reconstructed	Measured	Reconstructed
60	82.5	83.6	86.4	86.4	83.6	81.8
100	88.3	89.0	93.2	93.1	88.0	87.4
120	91.4	91.7	95.7	96.6	89.7	89.8

is mainly due to the difference in wheel roughness levels at each site. The reconstruction of the general shape of the spectrum is acceptable, and in the 1250 Hz and higher frequency bands the agreement is very reasonable. Moreover, the reconstructed overall A-weighted level, given in the legend, differs only by 0.5 dB from the measured level. Similarly, Fig. 14 presents measured and reconstructed pass-by levels at the second site, using vehicle data from the first site. The agreement is of the same quality is in Fig. 13. The difference of reconstructed and measured total A-weighted level here is 1.1 dB.

Similar calculations for 60 and 120 km/h are summarized in Table 5. This table shows that in general the measured and reconstructed sound levels agree within about 1 dB. Despite some larger differences in individual one-third octave bands, the reconstruction can be considered as meaningful.

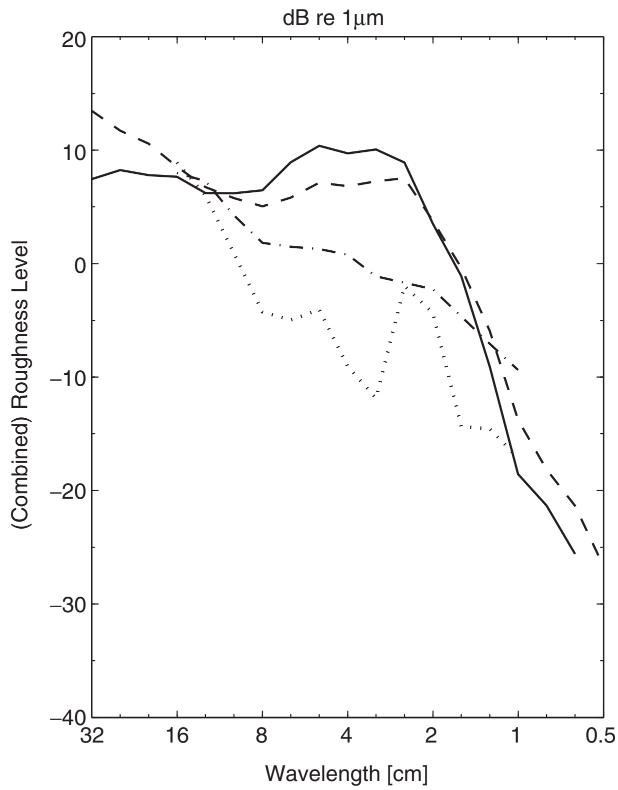

Fig. 11. Combined effective roughness for G50 Freight from pass-by at two sites: ——, Site 2; - - - - -, Site 1 (compare Fig. 5: · · · · · · ·, rail roughness Site 2 from direct measurement; –·–·–, rail roughness Site 1.

6.3. Conclusions of validation measurements and discussion

1. The determination of vehicle and track transfer functions is accurate to within ± 3 dB in each one–third octave band. This accuracy is validated by comparison with directly measured transfer functions.
2. Combination of the total effective roughness, total transfer function and train speed gives a reconstruction of the pass-by sound pressure spectra. This reconstruction is accurate to within, on average, ± 0.6 dB(A). This accuracy is validated by comparison with pass-by sound pressure spectra at 60, 100 and 120 km/h for three vehicles.
3. The transfer function measurement on a particular site is repeatable to within ± 1.5 dB in each one-third octave band.
4. As a consequence of the conclusions 1–3, the estimate of the separated vehicle and track noise contribution at a particular site can expected to be accurate within about ± 3 dB in each one-third octave band, and within about ± 1 dB for the *A*-weighted overall spectrum level.
5. The vehicle transfer function measurement is repeatable at two different sites to within about ± 2 dB.
6. The reconstruction of pass-by at a site using vehicle data acquired at another site was ± 4 dB for individual one-third octave bands and, on average, ± 1 dB in terms of *A*-weighted overall level.
7. The method applied to a pass-by measurement with a reference vehicle enables the determination of the track transfer function and vehicle transfer function of other vehicles.

The vehicle transfer function of the reference vehicle should preferably be at least 6 dB below the track transfer function in each one-third octave band or at least 6 dB lower than the vehicle transfer of the other vehicle. That will ensure the contamination by the reference vehicle radiation in the energy sum of vehicle and

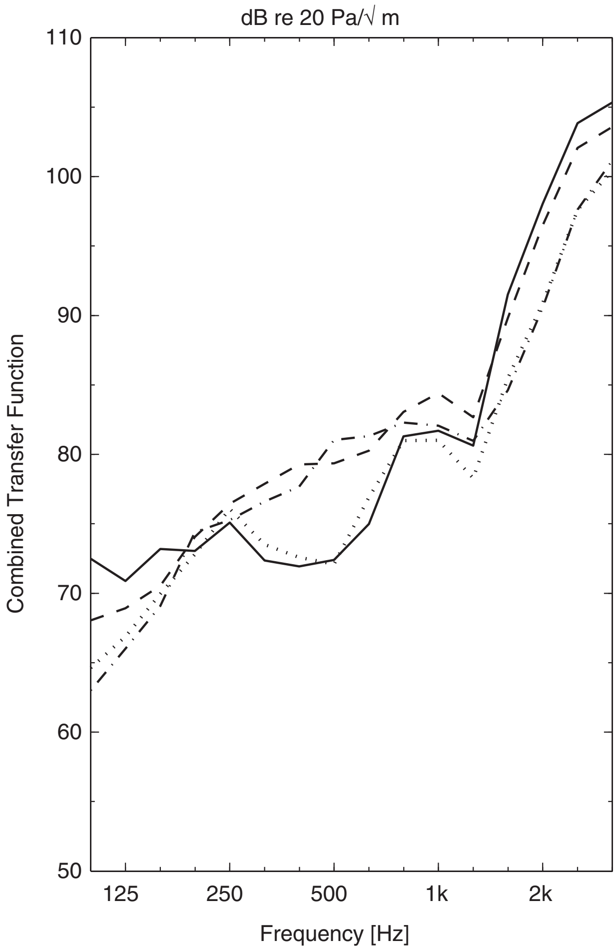

Fig. 12. Combined transfer function for G50 Freight wagon: ——, from pass-by measurement at Site 2; - - - - -, Site 1. Combined transfer function for Novatrans 'reference' wagon pass-by measurement: · · · · · · ·, Site 2; –·–·–, Site 1.

track noise to be less than 1 dB. A Novatrans container carrier wagon with 730 mm diameter wheels was found to satisfy this restriction for the frequency range up to 2 kHz. A vehicle with even smaller wheels, e.g. 680 mm would be expected to meet these requirements for higher frequencies as well.

Provided that the rails are sufficiently smooth, e.g. below the prEN-ISO 3095 (January 2001) norm, the method for combined roughness determination can be used to determine wheel roughness from pass-by measurements. The current example yields results for the wavelength range from 1 to 8 cm for block braked wheels.

7. Conclusions

Based on well-known rolling noise principles, the pass-by rolling noise of trains can be decomposed into a vehicle transfer function, a track transfer function, wheel roughness, rail roughness and train speed. Using these quantities, it is possible to separate vehicle and track radiation. In addition, it is possible to characterize a vehicle independently from the track using its transfer function and roughness. Similarly, the track is characterized by its own roughness and transfer function. It has been shown that vehicle data could be transferred from one site to another and that track data could be transferred from one vehicle to another.

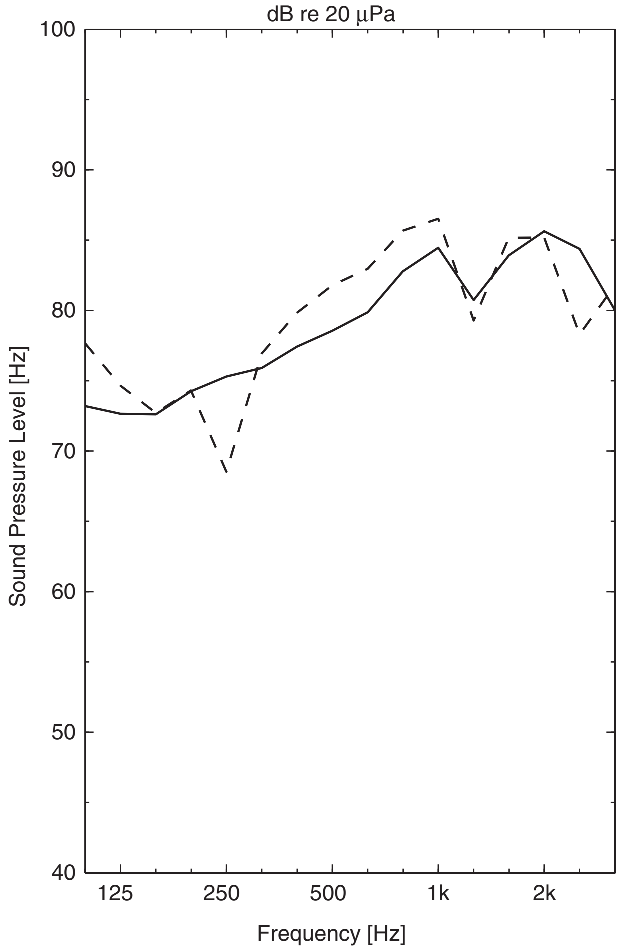

Fig. 13. Measured sound pressure levels at 7.5 m for 100 km/h for pass-by of G50: ——, freight wagon on Site 1, total *A*-weighted level of 93.2 dB(A); - - - - - -, reconstructed spectra for Site 1 using wheel roughness and vehicle transfer functions taken at Site 2, total *A*-weighted level of 93.7 dB(A).

Furthermore, measurement methods have been developed that derive these quantities from fairly simple trackside pass-by measurements using, in principle, one accelerometer, a wheel trigger device and one microphone. These include the combined total effective roughness from the rail vibration signal during pass-by and the vibro-acoustic transfer function between effective roughness and sound pressure from a pass-by. The accuracy was about ± 3 dB for individual one-third octave bands. Based on pass-by data estimates can be obtained for the transfer function of the track, by using a pass-by of a quiet 'reference vehicle'; the spatial decay of the track, giving agreement of ± 1.5 dB with conventional hammer measurements; the transfer function of the vehicle, by using energy difference or a quiet 'reference track'; and on a smooth track, wheel roughness for individual wheels, all wheels on a vehicle or a group of vehicles.

A validation exercise has shown that using these measured functions, the overall *A*-weighted pass-by sound pressure level of various combinations of vehicles and tracks could be reconstructed with an accuracy of ± 1 dB.

The approach presented is only valid for rolling noise. When there are significant levels from other noise sources, such as traction, braking, squealing or aerodynamic noise, these should be dealt with separately.

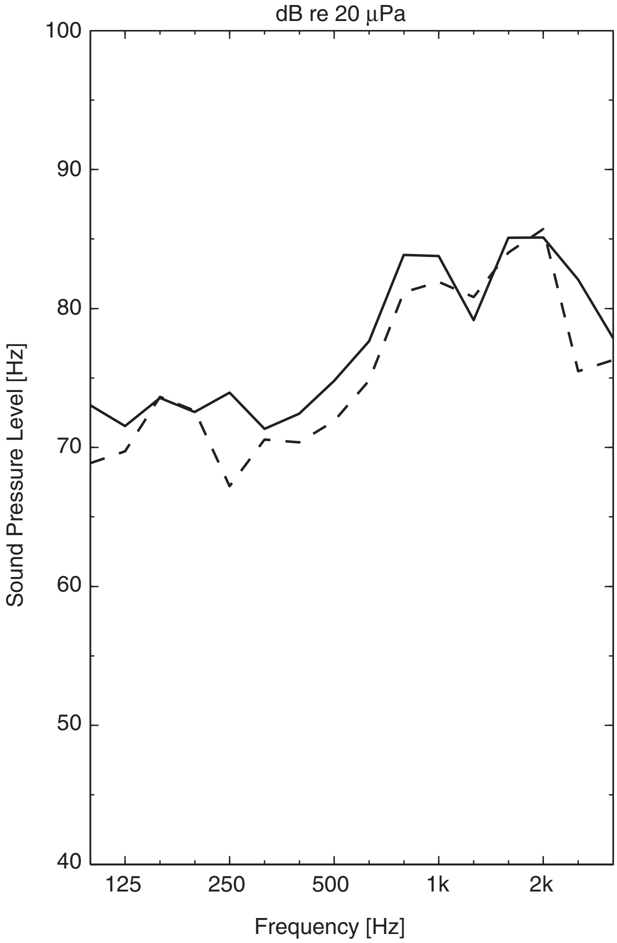

Fig. 14. Measured sound pressure levels at 7.5 m for 100 km/h for pass-by of G50: ——, freight wagon on Site 2, total *A*-weighted level of 92.5 dB(A); - - - - - -, reconstructed spectra for Site 2 using wheel roughness and vehicle transfer functions taken at Site 1, total *A*-weighted level of 91.4 dB(A).

Table 5
Cross-consistency test for two sites at Caen (wooden sleepers and monobloc concrete sleepers) for the G50 freight wagon

Speed (km/h)	Site 1, G50 Freight		Site 2, G50 Freight	
	Measured (tr3)	Reconstructed vehicle data from Site 2	Measured (tr2)	Reconstructed vehicle data from Site 1
60	86.4	87.0	83.1	82.5
100	93.2	93.7	92.5	91.4
120	95.7	97.3	96.7	96.0

Measured *A*-weighted pass-by sound pressure levels at 7.5 m in dB and reconstructed levels using roughness spectra, train speed and transfer functions. For the reconstruction for Site 1, the vehicle function and vehicle roughness is taken from Site 2, and vice versa.

Acknowledgements

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