Journal of Sound and Vibration (2000) **231**(3), 595–609
doi:10.1006/jsvi.1999.2547, available online at http://www.idealibrary.com on IDEAL®

IMPROVED MEASUREMENT METHODS FOR RAILWAY ROLLING NOISE

M. G. DITTRICH AND M. H. A. JANSSENS

TNO Institute of Applied Physics, Postbus 155, 2600 *AD Delft, The Netherlands*

(*Received in final form* 23 *September* 1999)

Some of the issues related to railway noise type testing are discussed and potential improvements to existing procedures are put forward. New and improved methods that also go beyond the scope of type testing are presented that help to characterize and analyze rolling noise more accurately. These methods are indirect measurement of total wheel–rail roughness, the use of an antenna for source location, and two new methods for separation of vehicle and track noise. Most of the work presented has been performed in the METARAIL project, which is focused on developing improved methods for type testing, monitoring and diagnostic methods for railway pass-by noise.

1. INTRODUCTION

In recent years, knowledge on railway noise control has increased to such an extent that practical measures for rolling stock and track can be implemented, in particular for wheel–rail rolling noise. Validated models such as TWINS [1] are available which allow noise assessment and optimization of track and wheel design. The introduction of low noise solutions and new legislation gives rise to the need for improved measurement methods for railway noise, which are accurate enough for acceptance testing (type testing) and methods that can be used to quantify the effect of individual noise control measures.

When measuring railway pass-by noise, differences in noise levels can occur due to a number of effects, leading to poor reproducibility. Rolling noise, which is often a predominant source, is influenced by wheel and rail roughness, train speed and the particular vehicle–track combination. It has been established in previous work [1] that the wheel, the rail and the sleeper are the major contributors to rolling noise, and that their contributions can vary. Consequently, either the track or the vehicle may dominate the total measured noise level. In turn, it is then difficult to assess the effect of noise control measures that may reduce vehicle noise but not track noise, or *vice versa*. Single microphone measurements are therefore inadequate to fully quantify the effect of acoustic devices such as bogie shrouds or wheel dampers.

In this paper, some of the issues related to type testing are discussed and potential improvements to existing procedures are put forward. Also new and

0022-460X/00/130595 + 15 $35.00/0

improved methods are presented that help characterize and analyze rolling noise more accurately. These are indirect measurement of total wheel–rail roughness, the use of an antenna for source location, and two new methods for separation of vehicle and track noise.

Most of the work presented has been performed in the METARAIL project, which is focused on developing improved methods for type testing, monitoring and diagnostic methods for railway pass-by noise (see [4, 6–11, 14–15]).

2. ISSUES RELATED TO TYPE TESTING

2.1. RECOMMENDED IMPROVEMENTS

Current type testing procedures [2, 3] for railway pass-by noise based on single microphone measurements needed improving due to lack of reproducibility of the test conditions. This can be done by giving a clearer specification of track conditions and measured quantities. A major issue is the fact that whereas type testing is supposed to characterize the noise caused by the vehicle in its normal operating condition, depending on the wheel and rail roughness and track/vehicle noise contributions, the track may be characterized instead. To characterize only the vehicle, one of the recommendations should be that track roughness should be well below that of the vehicle, and the vehicle noise contribution should greatly exceed track noise, or somehow be separated from it. Track noise can dominate overall pass-by noise levels, and can vary in level depending on track behaviour due to variable pad stiffness, track damping and sleeper support. This gives rise to lack of reproducibility between different sites.

These issues have been examined in detail and recommendations for improvements to the type testing procedures have been given in reference [4], which may in part be referred to in future versions of the type testing standard [5]. Some of the recommendations are summarized briefly below, of which 1–3 are covered in this paper:

1. Add a procedure for measuring rail roughness, and an upper limit of roughness a test site should not exceed.
2. Introduce the derived quantities vehicle noise and track noise and provide procedures to determine these.
3. Describe how track parameters should be characterized *in situ*.
4. Measure equivalent sound pressure levels and related quantities instead of maximum levels.

The use of vertical railhead vibration has been shown to be an especially useful additional parameter to separate track noise, to monitor wheel/rail roughness, and to characterize track properties [6–8]. A detailed procedure has been described by the CEN/TC256 working group to measure site rail roughness directly and to specify rail roughness limits for type testing, to ensure rail roughness conditions suitable for type testing purposes [5]. The indirect techniques discussed in this paper may provide alternatives for direct roughness measurement. Requirements

TABLE 1

Indicative parameter sensitivity on total rolling noise for conventional track systems

Parameter	Parameter value for minimum noise level	Parameter value for maximum noise level	Level difference for min. and max. parameter value
Rail type	UIC 54 E	UIC 60	0·7 dB(A)
Static pad stiffness	5×10^9 (N/m)	10^8 (N/m)	5·9 dB(A)
Pad loss factor	0·5	0·1	2·6 dB(A)
Sleeper type	Bi-block	Wooden	3·1 dB(A)
Sleeper distance	0·4 (m)	0·8 (m)	1·2 dB(A)
Ballast stiffness	10^8 (N/m)	3×10^7 (N/m)	0·2 dB(A)
Ballast loss factor	2·0	0·5	0·2 dB(A)
Wheel offset	0 (m)	0·01 (m)	0·2 dB(A)
Rail offset	0 (m)	0·01 (m)	1·3 dB(A)
Wheel roughness	Smoothest	Roughest	8·5 dB(A)
Roughness of uncorrugated rails	Smoothest	Roughest	0·7–3·9 dB(A)
Train speed	80 (km/h)	160 (km/h)	9·4 dB(A)
Wheel load	125000 (kg)	5000 (kg)	1·1 dB(A)
Air temperature	10°C	30°C	0·2 dB(A)

for specifying track dynamics *in situ* have also been put forward. Methods related to wheel/rail roughness and source separation are presented in sections 3–6. Track dynamics characterization is discussed in Section 7.

2.2. OVERALL PARAMETER SENSITIVITY

A parameter sensitivity study [7] revealed the significance of some parameters for the measurement of pass-by rolling noise. This analysis was based on calculations with the TWINS package, acoustics theory, literature and measurement data. The parameters examined influence the noise radiated by the track, thereby affecting the total noise level, and the ratio of track to vehicle noise. The values given in Table 1 are indicative of these effects.

Train speed, wheel and rail roughness and pad behaviour have the most substantial effect on track noise. Other factors have less effect but, in combination, can still cause substantial differences between measurements at different sites.

3. INDIRECT ROUGHNESS MEASUREMENT FROM RAIL VIBRATION

3.1. DIRECT ROUGHNESS MEASUREMENT

Direct roughness measurement refers to measurement procedures that scan the wheel or rail surface directly [15]. The most frequently used systems employ a mechanical needle-like sensor, which takes samples at short intervals, for instance 0·5 mm, along a measurement line in the direction of travel. Although the effect of the contact patch is not included in such measurements, they do provide useful data which can be processed for calculation purposes [1]. The discretized roughness amplitude signal is conditioned and transformed into the frequency domain and presented in 1/3-octaves. Such systems are still the most accurate available, although for rail roughness measurements several rail sections have to be measured separately and processed to obtain an estimate for a section of track.

3.2. INDIRECT ROUGHNESS MEASUREMENT

A new indirect measurement technique for estimating total roughness from rail vibration during pass-by has been developed [4, 9]. Total roughness is the energy sum of wheel and rail roughness. The technique uses vertical railhead vibration, and can provide an estimate for roughness spectra of vehicle groups, bogies and, under the right conditions, of individual wheels, as long as the wheel roughness exceeds the rail roughness. The method has been tested on existing data indirectly, and compared to direct measurement results. It was found that the indirectly measured spectra fell within the spread seen in directly measured roughness data. The measured parameters are vertical railhead vibration, train speed, and vertical spatial decay of the track. Current recommended train speeds during indirect roughness measurements are 80 km/h and lower, due to signal conditioning considerations, and five measurement positions per rail are recommended to characterize fully the roughness over the whole wheel circumference.

According to TWINS calculations [9] the indirect roughness measurement predicts the total roughness within an accuracy of 5 dB assuming the following conditions:

— the wheel radius is greater than 0·35 m,
— the static wheel load is about 50 kN,
— the rail vibration decay is updated on-line.

For smaller wheels or wheel loads, the method can be adjusted.

The total roughness for a single wheel passage is directly related to vertical railhead vibration, as described in reference [9]. A simplified formula for this relation is given here, with vibration expressed in terms of velocity:

$$L_{rtot}(f) = L_{veq}(f) + 10\,\lg\left(\frac{VTD(f)}{8{\cdot}68}\right) + C_{23}(f) - 10\,\lg(2\pi f)$$

$$= L_{v\,\max}(f) + C_{23}(f) - 10\,\lg(2\pi f) \qquad (1)$$

where $L_{rtot}(f)$ is the total roughness spectrum (dB re 10^{-6} m), $L_{veq}(f)$ the equivalent velocity vibration spectrum (dB re 10^{-6} m/s), $L_{vmax}(f)$ the maximum velocity vibration spectrum (dB re 10^{-6} m/s), V the train speed (m/s), T the passage interval (s), $D(f)$ the vertical spatial decay spectrum (dB/m), and $C_{23}(f)$ the

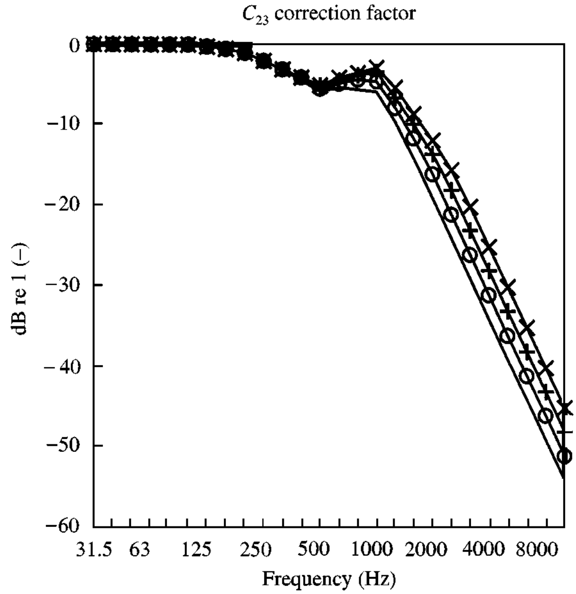

Figure 1. Correction factor C_{23} for contact filter and contact vibration to apparent roughness. ——, 80 km/h; —○—, 100 km/h; —+—, 120 km/h; —×—, 160 km/h.

conversion spectrum for contact filter and contact vibration to apparent roughness, shown in Figure 1 for given speeds (calculated with TWINS).

Equation (1) gives an estimate for the absolute value of the total roughness from railhead vibration, train speed, spatial decay and contact transfer functions. As it is sensitive to spatial decay, pad stiffness and contact geometry, it is recommended that the following relative formula is used if possible:

$$L_{rtot2}(f) - L_{rtot1}(f) = L_{v,rail,2}(f) - L_{v,rail,1}(f), \tag{2}$$

where L_{rtot1}, L_{rtot2} are the total roughness spectra as a function of frequency at one point for two different pass-bys (wheel, bogie or train), and $L_{v,rail,1}$, $L_{v,rail,2}$ are velocity vibration spectra, for either equivalent levels or L_{vmax} levels for the corresponding pass-bys. This relation eliminates the need to know other parameters, and can be used if an initial roughness level $L_{rtot,1}$ is known.

Three to five measurement positions are recommended to obtain a representative average L_{vmax} as the distance covered by one accelerometer is only about 60 cm. These positions can be adjacent or distributed over a greater distance than shown in Figure 2. This reduces the sensitivity to spatial decay.

The current assessment of the indirect roughness technique is that it is very promising, time-saving and potentially inexpensive, as measurements can be performed during pass-bys of large numbers of wheels, and no special equipment other than standard accelerometers and frequency analysers are needed.

One of the obvious applications of indirect roughness measurement is to obtain fast on-line information on roughness levels on whole trains, without taking the train out of operation. By measuring the railhead vertical vibration level L_v over

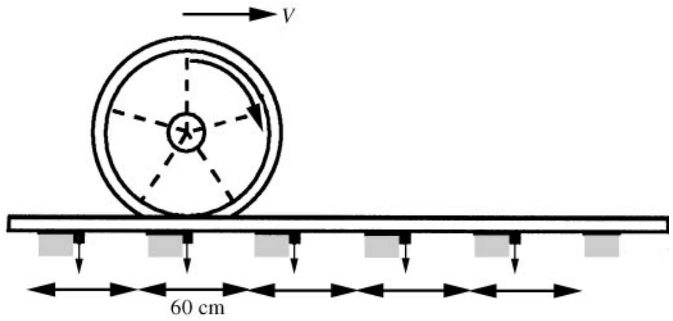

Figure 2. Indirect roughness measurement with five transducers.

individual wheels, bogies, wagons or whole trains at a particular speed, differences in roughness can be derived, as long as wheel roughness exceeds rail roughness by 6–10 dB (10 dB difference gives an error smaller than 0·5 dB).

A less obvious, but extremely useful application of the indirect technique is to detect an upper limit for rail roughness at a particular site, without using a direct rail roughness measurement device. This is done by monitoring railhead vibration for varying traffic, and selecting the lowest vibration levels at a given train speed. As the total roughness consists of the energy sum of wheel and rail roughness, the rail roughness has to be equal to or below the lowest peak in total roughness caused by very smooth wheels.

The upper limit of rail roughness $L_{r,\,rail,\,max}(\lambda)$ is given by

$$L_{r,\,rail,\,\max}(\lambda) = \min_i \left(L_{rtot,\,i}(\lambda)\right), \quad i = 1, \ldots, n, \tag{3}$$

where $L_{rtot,\,i}$ is the total roughness of pass-by i (wheel, bogie, wagon or train), λ the roughness wavelength (m), and n the number of pass-bys, which may be at various speeds.

3.3. ALTERNATIVE FOR MEASURING RAIL ROUGHNESS IN TYPE TESTING

For type testing it should be feasible to apply a simplified indirect roughness measurement to check the rail roughness. Instead of measuring the absolute rail roughness in detail it is sufficient to know whether wheel roughness exceeds rail roughness by more than about 10 dB, in the frequency region relevant for A-weighted levels at a given speed. So the condition

$$L_{r,\,wheel} \geqslant L_{r,\,rail} + 10 \tag{4}$$

can be satisfied if

$$L_{veq,\,testvehicles}(f) \geqslant L_{veq,\,smoothwheel}(f) + 10 \tag{5}$$

for identical speed. So by comparing railhead vibration between a train with wheels "10 dB smoother" than the test train, direct rail roughness measurement can be avoided. This condition should primarily hold in the A-relevant frequency region, where the noise spectrum will be seen to be within 10 dB of its maximum. The procedure can be performed specifically at the train speeds of the type test.

4. SOURCE LOCATION AND QUANTIFICATION WITH AN ANTENNA

An existing antenna measurement system was improved specifically for railway noise applications (see reference [10]) in METARAIL. An antenna provides a means of visualizing the sound intensity close to the train, allowing source location and quantification. Measurements were performed on the METARAIL test train at various speeds using a T-array with 48 microphones positioned at 2·7 m from the track centreline, and using the swept focus technique (see reference [10]). The test train consisted of three types of freight wagons in groups of four, with a locomotive at each end and quiet disc-braked passenger coaches near the quietest freight wagons. The freight wagons were hopper wagons for gravel (cast iron block-braked), flat car transport wagons (composite block-braked) and flat container wagons with shrouded bogies (disc-braked). An example of measured data from the test train at 80 km/h is shown in Figure 3. These measurements and earlier measurements have shown that the emission level of the superstructure of a freight train travelling at around 80 km/h was at least 15 dB below that of the wheels and track (see Figure 3). The effect of the bogie shrouds is clearly visible, especially in the 1 and 2 kHz octave bands. This type of result is only obtainable at short distances. Analysis results from the antenna at 7·5 m showed somewhat less detail.

Aspects of the application to railway noise that currently limit the antenna performance beyond the theoretically achievable performance, are

— ground reflections;
— distributed sources on the upper part of the train in the presence of strong concentrated sources on wheels and track;
— the short distance to the source which gives higher spatial resolution, but increases focusing errors outside the focal point.

Feasible applications of antenna systems for railway noise are currently the following:

— determination of the sound emission of a separate wheel–rail combination;
— determination of the total emission of the superstructure and the total wheel–rail emission;
— location of source distributions on the superstructure when their emission level per square meter is not more than 10–15 dB below that of the wheels.

Resolution limitations are found for low frequencies (below 250 Hz) or for closely positioned sources such as wheels and rails. This is fundamental to the principle of most antenna systems. Nevertheless, there is still a major benefit in visualizing the sources on a passing train.

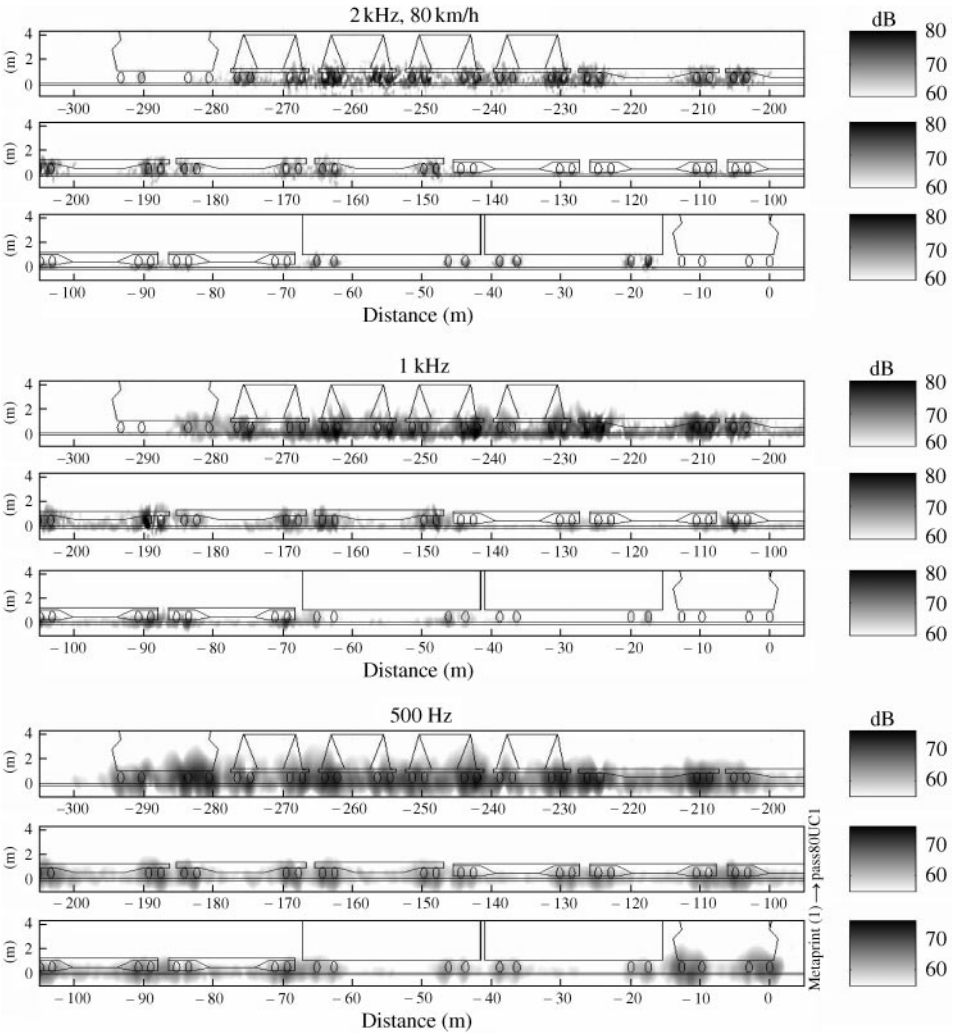

Figure 3. Antenna images of the METARAIL test train at 80 km/h, 2 kHz, 1 kHz and 500 Hz octave bands, measured with T-array at 2·7 m distance from the track centreline.

5. SEPARATION OF TRACK NOISE WITH THE EQUIVALENT FORCES METHOD

A new measurement technique was developed in METARAIL [11], to obtain the noise contribution from the track. It involves measuring multiple vibro-acoustic transfer functions on the track, and then deriving the track contribution from multi-channel rail vibration measurements during pass-by. An advantage of this approach is that the track noise can totally and explicitly be separated from the wheel/vehicle noise. No contribution of wheel noise is present in the final result. A disadvantage of the method could be that a part of the measurements is performed without a train present on the track, which could affect track dynamics.

Nevertheless, the technique is considered to be rather robust and the impacts of these effects are assumed to be limited. The method is an application of the so-called "equivalent forces method" [12, 13] especially adapted and implemented for track noise analysis. The equivalent force technique is a substitution source technique; the actual excitation of a system is replaced by an artificial excitation which produces the same structural response. The radiated sound is then determined using the relation between the artificial excitation and the radiated sound.

The steps in the equivalent force method are as follows:

1. Select a number (n) of positions at which the equivalent force is to be applied. The forces are stored in vector $\{F\}$,
2. Select a number of (m) response positions to monitor the structural response of the system; the responses are stored in vector $\{a\}$.
3. Select a number (p) of positions to determine the airborne sound response. The airborne responses are stored in vector $\{p\}$.
4. Determine transfer functions between excitation $\{F\}$ and responses $\{a\}$. These functions form matrix $[A]$.
5. Determine transfer functions between excitation $\{F\}$ and responses $\{p\}$. These form matrix $[H]$.
6. Determine the operational response $\{a\}_{\text{operational}}$.
7. Derive equivalent forces from matrix equation $[A]\{F_{\text{eq}}\} = \{a\}_{\text{operational}}$.
8. Derive sound pressure estimates using $\{p\}_{\text{estimated}} = [H]\{F_{\text{eq}}\}$.

In references [12, 13] it is shown that this approach can be applied successfully for sound path quantification purposes. A new development for railway application is to take the moving excitation of the train into account.

Although this indirect technique can be characterized as an advanced tool for railway noise analysis, standard measurement equipment and procedures are employed. Measurements can be performed using ordinary two- (or multichannel) FFT-analysers, in combination with digital recorders. Specific expertise and software is, however, required for the data processing and interpretation.

The technique has been used during field measurements, illustrating how track noise emission can be analyzed during a train pass-by. It enables a quantification of the track source strength in terms of sound power level per metre track. Furthermore, details on track radiation and three-dimensional directivity can be obtained and visualized. It can therefore be expected that the method will be able to assess in detail the effect of particular measures applied to a train or track or reduce noise emission levels. By quantifying both track noise and total noise the vehicle contribution can also be assessed.

The method has been applied extensively [11], resulting in much (visual) detail on track noise (Figure 4). Simplifications of the method can be made, which can decrease the measurement effort significantly. Based on this method, a rather simple measurement method can be derived to measure the relation between rail vibration and total sound radiation of the track only. Such a measurement technique could serve in type testing measurements in order to separate track and

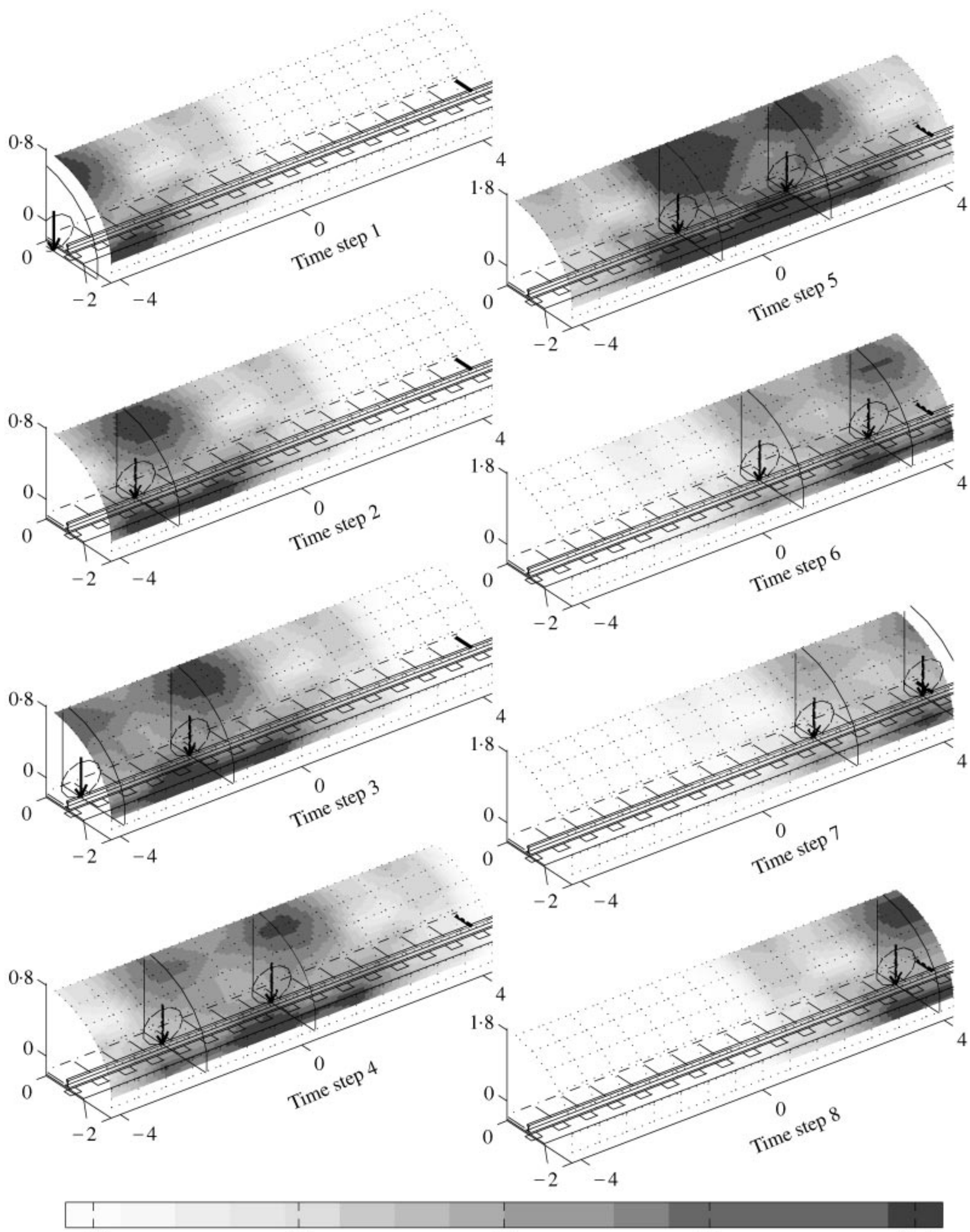

Figure 4. Example of reconstructed sound pressure distribution over the measurement surface caused by the track only, at successive time intervals, in the 1 kHz octave band. One bogie is passing the measurement section. The wheel positions are indicated by arrows. Passenger train SGM at 120 km/h.

vehicle noise. This technique could be an alternative for the method using a reference vehicle described in the following section. Further research on this point is required.

6. SEPARATION OF TRACK NOISE BY USING A REFERENCE VEHICLE

6.1. METHOD DESCRIPTION

Another relatively simple method for separating track and vehicle noise contributions under operational conditions was devised during the METARAIL project. The main advantages of the method are:

- a simple procedure that produces "vehicle noise" and "track noise" besides the total pass-by noise;
- results are fully representative for operational conditions;
- no restriction on wheel or rail roughness;
- no roughness measurement is required;
- the reference function is characteristic of the vibro-acoustic track behaviour.

The method is based on the assumption that vertical railhead vibration is a fairly good indicator for the excitation in the wheel–rail contact patch, and that the vibro-acoustic behaviour of the track remains constant in time.

Sound pressure and vertical railhead vibration are measured simultaneously. First, the track behaviour is determined in a separate reference measurement using specially prepared reference vehicles which radiate substantially less noise than the track, irrespective of the wheel and rail roughness levels. Then the vehicle and track noise levels can be derived for arbitrary vehicles which have a higher vehicle-to-track noise ratio than the reference vehicle.

The method is applicable for any track–vehicle combination, as long as the 1/3-octave SPL spectrum of the reference vehicle is at least 10 dB below that of the track. If the 10 dB difference cannot be achieved, either lower accuracy should be accepted or alternative measurement procedures should be applied. There is no restriction on roughness levels of the vehicle or the track, although very poor surface conditions and unwelded rail joints must be avoided. The method is most suited for microphone distances of 7·5 m or less, as at larger distances the low vehicle contribution may be contaminated by adjacent noisier vehicles. Consequently, at larger distances such as 25 m a longer set of reference vehicles is required. The accuracy of the vehicle noise level is 0·5 dB(A) if the reference vehicle is at least 10 dB(A) quieter than the track.

A track reference function L_{Href} is measured during passage of several reference vehicles, defined as

$$L_{Href}(f) = L_{ptr,ref}(f) - L_{vr,ref}(f), \tag{6}$$

where $L_{ptr,ref}$ is the track sound pressure spectrum at 7·5 m and $L_{vr,ref}$ is the railhead vertical vibration velocity spectrum, with both spectra in 1/3-octaves, either both linear or both A-weighted.

There should be at least 3–4 reference vehicles with a total length of at least 45 m. These vehicles must be at the end of the train, without any trailing vehicles or locomotive, unless it can be shown that no contamination of the noise from adjacent vehicles occurs. Data are acquired from the second reference vehicle to the last, at 80 km/h and optionally at other speeds (Figure 5). The track reference function is characteristic of the track type and the local conditions. The effect of variation in local conditions can be reduced by repeating the measurement at two or three track cross-sections.

6.2. REQUIREMENTS FOR THE REFERENCE VEHICLE

The reference vehicle (see Figure 6) should be at least 10 dB quieter than the track over the frequency range of interest. On conventional track, this can be achieved by fitting the wheels with absorbent partial enclosures down to 10 cm above the rail, and fitting dampers on the wheels. If possible, and preferably, small wheels can be used with a diameter of 40 cm or less. The reference vehicle must be quieter than the track, and the difference must be quantified.

This can be done by applying the equivalent forces method described previously, or by reciprocal measurement methods on a stationary vehicle; alternatively, calculation of the track noise using TWINS could be performed, with rail vibration and *in situ* track parameters as input. This last option is however prone to the errors of input assumptions and not strictly a measurement procedure.

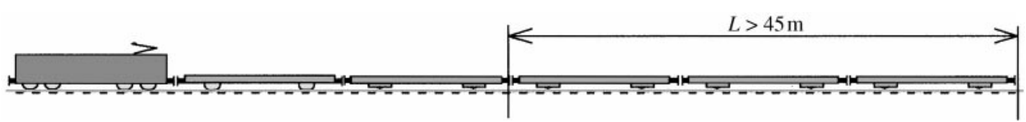

Figure 5. Train configuration for track reference function measurement; at least three reference vehicles with at total length of at least 45 m, positioned at the end of a train, are recommended.

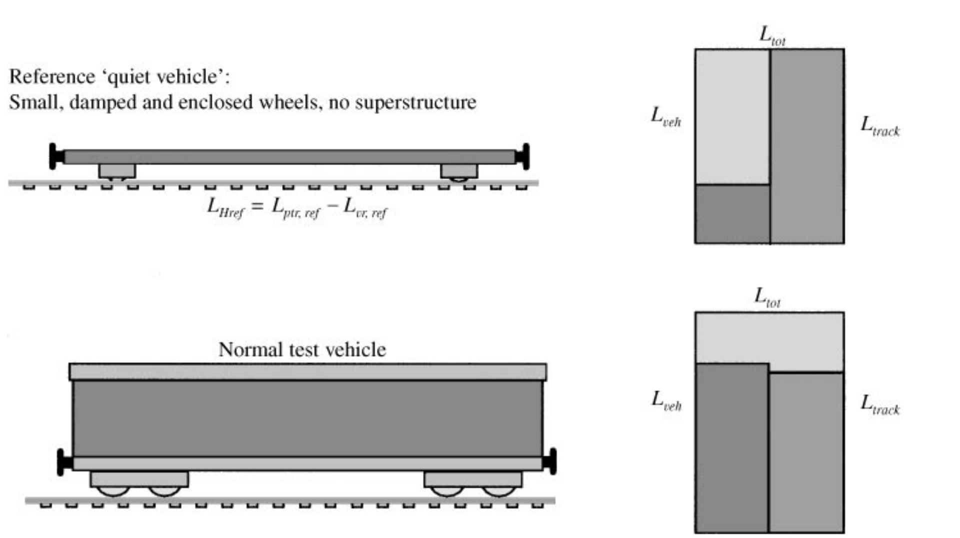

Figure 6. Schematic illustration of possible reference vehicle (top) in comparison with normal test vehicle (below). The noise contribution in the total noise level should be substantially lower for the reference vehicle.

6.3. DETERMINING TRACK AND VEHICLE NOISE LEVELS

For any train passage at the same location, the track and vehicle noise spectra can now be derived as follows:

$$L_{ptr}(f) = L_{Href}(f) + L_{vr}(f) \tag{7}$$

and

$$L_{pveh}(f) = 10\,\lg(10^{L_{ptot}(f)/10} - 10^{L_{ptr}(f)/10}) \tag{8}$$

processed as unweighted 1/3-octave spectra, and afterwards applying A-weighting to L_{ptr} and L_{pveh}.

7. CHARACTERIZATION OF TRACK DYNAMICS

Track dynamic behaviour has major influence on the noise contribution of the track, and therefore influences reproducibility when the track noise exceeds vehicle noise. For this reason, it is necessary to characterize the track. The way in which this can be done may depend on the further use of the quantities measured.

Modelling experience indicates that for the track dynamic behaviour the most relevant parameters are rail geometry and material, pad static and dynamic stiffness and loss factor, fastener type, sleeper geometry, material and distance. If these parameters are known, track response calculations can be made with models such as TWINS, based on nominal input data.

At any specific site, the values of pad and fastener behaviour may vary from nominal values, depending on local variations due to sleeper contact, alignment, age and maintenance. Pad behaviour can also be affected by temperature. The real track can be characterized *in situ* by measuring, under stationary conditions on unloaded or loaded track:

— vertical and horizontal railhead impedance (contains pad stiffness and damping);
— vertical and horizontal spatial decay (takes pad and fastener behaviour into account).

Impedance (or mobility) and spatial decay can be measured by means of impact response measurements in the frequency region 100–8000 Hz.

More representative characteristics can be obtained during a pass-by by measuring vertical vibration isolation and vertical and horizontal railhead vibration. Dynamic pad stiffness and damping can be estimated from vibration isolation, whilst spatial decay can be estimated from vertical and horizontal railhead vibration. The reference function defined in Section 6.1 could also be adopted as an overall track characteristic function, as it contains all relevant track properties, representative of operational conditions. Both vibration isolation and the track reference function should be averaged over at least three positions along the track, as substantial variation is often found in measured data.

8. CONCLUSIONS

New and improved methods for indirectly measuring roughness and for separating track and vehicle noise have been presented, some of which can be proposed for type testing purposes. Further testing and validation of the methods in practice is still required. Now that some of the proposed techniques allow separation of track and vehicle noise, the question of which values to use when comparing noise emission of two different vehicle types is relevant. Instead of comparing total noise levels it would seem more appropriate to compare the vehicle contributions at given speeds, to indicate whether the total noise level is dominated by track or vehicle noise, and to state whether wheel roughness exceeds rail roughness.

ACKNOWLEDGEMENTS

This work has been performed within the METARAIL project EC/DGVII (Contract RA-97-Sc.1080) which deals with type testing, monitoring and diagnostic measurement methods for railway pass-by noise. The project partners are Schreiner Consulting (A, Coordinator), Psi-A Consulting (A), ÖBB (A), IPSE Srl (I), NS (NL), ERRI and TNO Institute of Applied Physics (NL). The project is partially funded by the European Commission DGVII whose support is gratefully acknowledged.

REFERENCES

1. D. J. Thompson and M. H. A. Janssens 1996 *TNO Report TPD-HAG-RPT-93-02, Delft*. TWINS theoretical manual, version 2.4.
2. *ISO/DIS 3095:1993 Draft Standard*. Measurement of noise emitted by railbound vehicles.
3. *CENT/TC 256 Working Group 3 1995 Draft Standard*. Railway applications/acoustics—measurement of external noise emitted by railbound vehicles.
4. M. G. Dittrich, J. Lub, G. Pollone and M. Kalivoda 1998 *METARAIL Report D10, TNO, Delft*. Methodologies for type testing and monitoring of railway noise (Task III.4).
5. *pr EN ISO 3095/1: 1998 E: Draft Standard*. Railway applications/acoustics—measurement of noise emitted by railbound vehicles.
6. M. G. Dittrich 1998 *Proceedings 2nd Conference on Abatement of Railway Noise Emissions—Freight Transport, Berlin*, 45–50. The METARAIL Project—new developments in railway noise emission measurement.
7. M. G. Dittrich, F. De Beer, G. Brero and G. Pollone 1997 *METARAIL Report D2, TNO, Delft*. Foundation for type testing and monitoring.
8. M. G. Dittrich, W. J. Van Vliet, J. Lub and G. Van Keulen 1997 *METARAIL Report D6, TNO, Delft*. Site calibrations.
9. F. G. De Beer, M. H. A. Janssens and M. G. Dittrich 1998 *METARAIL Report D8, TNO, Delft*. Indirect roughness measurement.
10. W. G. J. Hoffmans, T. C. Van Den Dool, A. P. Berkhoff and M. G. Dittrich 1998 *METARAIL Report D3b, TNO, Delft*. Antenna systems for railway noise analysis.
11. M. H. A. Janssens and C. M. Langeveld 1998 *METARAIL Report D4, TNO, Delft*. Pass-by spatial track vibration: indirect determination of total track noise contribution (Task II.3.2).

12. J. W. VERHEIJ 1997 *International Journal of Acoustics and Vibrations* **2**, 11–20. Inverse and reciprocity methods for machinery noise source characterization and sound path quantification. Part 1: sources.
13. J. W. VERHEIJ 1997 *International Journal of Acoustics and Vibrations* **2**, 103–113. Inverse and reciprocity methods for machinery noise source characterization and sound path quantification. Part 2: transmission paths.
14. M. G. DITTRICH, N. A. KINNEGING, G. BRERO, R. KAINBERGER and M. WIRNSBERGER 1997 *METARAIL Report D1, TNO, Delft*. Review of measurement methods for railway pass-by noise.
15. M. G. DITTRICH, F. J. W. BIEGSTRAATEN, E. J. J. DOPPENBERG and W. J. VAN VLIET 1997 *METARAIL Report D5, TNO, Delft*. Diagnostic tools and methods for measurement of railway noise—direct wheel roughness estimation.