VTN: A VALIDATED METHOD TO SEPARATE TRACK AND VEHICLE NOISE AND TO ASSESS NOISE REDUCTION MEASURES

Edwin Verheijen
Marco Paviotti
AEA Technology Rail BV
Postbus 8125
3503 RC Utrecht
Netherlands

Abstract

Within the European project STAIRRS, new methods and tools have been developed to address particular needs in the measurement and characterisation of railway noise. The Vibro-acoustic Track Noise method (VTN) is one of these methods. It is capable of separating the noise radiated by the train from the noise radiated by the track.

The method uses a small number of acceleration signals from the rails and sleepers to calculate the energy radiation from the track. By measuring the total noise emitted by vehicle and track, it is possible to calculate the vehicle contribution as well. The method has been validated in the STAIRRS project and its accuracy has been assessed. Comparisons with results from TWINS calculations give further information about the accuracy of the method.

The VTN-method has been programmed as a PC-based analysis tool. The tool has demonstrated its capabilities in the assessment of noise reduction measures. It clearly visualises the extent to which a measure acts on either the vehicle emission or the track emission. This makes it possible to assess the effect of that measure for combinations of other trains and tracks that were not tested. If the effect on the total noise is rather small (< 2 dB(A)), studying the VTN results can point out whether the effect is real.

Other applications of VTN are acceptance and limit conformance testing and the collection of emission data (monitoring). The separated results make it possible to attribute the responsibility of railway noise emission to the track maintainer on the one hand and the train operator on the other hand.

Key words: railway noise, measurement technique, source separation, TWINS

1. Introduction

Since the 1990s, the national railway administrations in Europe are separating their internal organisation structure into track management and train operation. A consequence of this policy is that the responsibility for railway noise is being reconsidered. There is a need to split railway noise into a part originating from the track and a part originating from the vehicles.

The European project STAIRRS (Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems, see [1]) has addressed this need, and has produced methods to characterise railway noise. This paper concentrates on the Vibro-acoustic Track Noise method (VTN). This measurement and analysis method is capable of separating pass-by noise into a track and a vehicle contribution. The goal of this paper is to introduce this method to a wider audience, to show its flexible and easy usage, and especially to demonstrate its strength in the assessment of noise reduction measures.

In the assessment of noise reduction measures, the question "which source is the predominant one?" is an important starting point, as source measures are only effective if the dominant sources are tackled. Until recently, to accurately answer this question, a model from the situation of interest was required, for instance with the engineering software TWINS [2]. The usage of this software is restricted to specialist users with detailed knowledge of wheel/rail dynamics, and for a reliable reference model expensive validation work (measurements and analysis) is required.

A different approach that may be used for source separation is to use microphone arrays, see for example [3]. Although array measurements help to identify the main noise sources of a passing train (along the train and also vertically), these techniques cannot separate rolling noise into wheel and rail contributions due to limited resolution.

The VTN method (Vibro-acoustic Track Noise) gives an answer to the separation question. The method is developed and validated by AEA Technology Rail in the STAIRRS project. It is a software package for PC, that analyses measurement signals into track and vehicle noise spectra. The method is easy to use and works with standard noise measurement equipment like microphones, accelerometers and an 8 channel recorder.

First, an outline of the method is given in Section 2. This section explains the basics and is appropriate for readers that do not measure or model noise themselves. In Section 3, the measurement set-up and preparation of signals is treated in detail, especially for those readers that intend to apply the method. Hereafter, the theory is explained in Section 4. Finally, in Section 5, the application of VTN in the assessment of source measures is demonstrated with application results.

2. Basic description of the method

The *Vibro-acoustic Track Noise* method basically calculates the vibration energy from the track using pass-by acceleration spectra taken at the rail in vertical and lateral direction. Additional accuracy is achieved if sleeper vibration spectra are available as well. Next, the rail and sleeper sound radiation energy is calculated. To this end the method uses, apart from the vibration spectra, visible track features like sleeper type and rail profile and a look-up table. The calculation is based on formulations that are embedded in the TWINS programme as well [2]. Hereafter, the propagation of track noise to a position at a short distance from the track (typically 7.5 m) is evaluated, taking account of absorptive properties of the ground. If the total noise at that distance is known as well, the vehicle noise contribution is estimated by subtraction.

In order to achieve the highest possible accuracy, a specific measurement procedure has to be followed. In combination with this procedure, the software package VTN provides an accuracy up to 1,5 dB(A) for the track noise contribution. But even for a large amount of historical sound and vibration date, a reasonable estimate of the train and track contributions are possible, as the measurement procedure features widely used and accepted measurement positions.

3. Measurement method

3.1 Measurement set-up

The measurement procedure that provides best separation results is the STAIRRS measurement protocol [4]. This protocol uses two measurement microphones, 5 (single axis) accelerometers and a trigger pulse generator. Figure 1 and Table 1 provide an overview of the measurement set-up. The minimum number of channels required for usage of VTN is three, but maximum (validated) accuracy is achieved using all channels.

sig.	signal type	position	usage for VTN
M1	total noise	7.5 m from track centre, 1.2 m above railhead	essential
M2	nearby noise	1.75 m from track centre, 0 m above railhead.	optional
V1	vertical rail acceleration	at mid-span under railfoot 1	essential
V2	vertical rail acceleration	at mid-span under railfoot 2	optional
L1	lateral rail acceleration	at mid-span, side of rail head 1	essential
L2	lateral rail acceleration	at mid-span, side of rail head 2	optional
S1	vertical sleeper vibration	on top of the sleeper, near the fastener	optional
T1	wheel trigger pulse	preferably 2 sleeper bays away from the cross section	for display only

Table 1: List of measurement signals. Optional signals are required for maximum accuracy.

On slab track, accelerometers V1 and V2 may be placed on top of the foot as close as possible to the web, while accelerometer S1 should be placed at 1/3 of the slab's width.

The measurement equipment (transducers and recorder) must provide preferably 40 dB dynamic range and 10 kHz frequency range. The STAIRRS prescription, stating that channel M2, V1 and L1 must pass a high-pass-filter *before* recording, does not apply for VTN measurements.

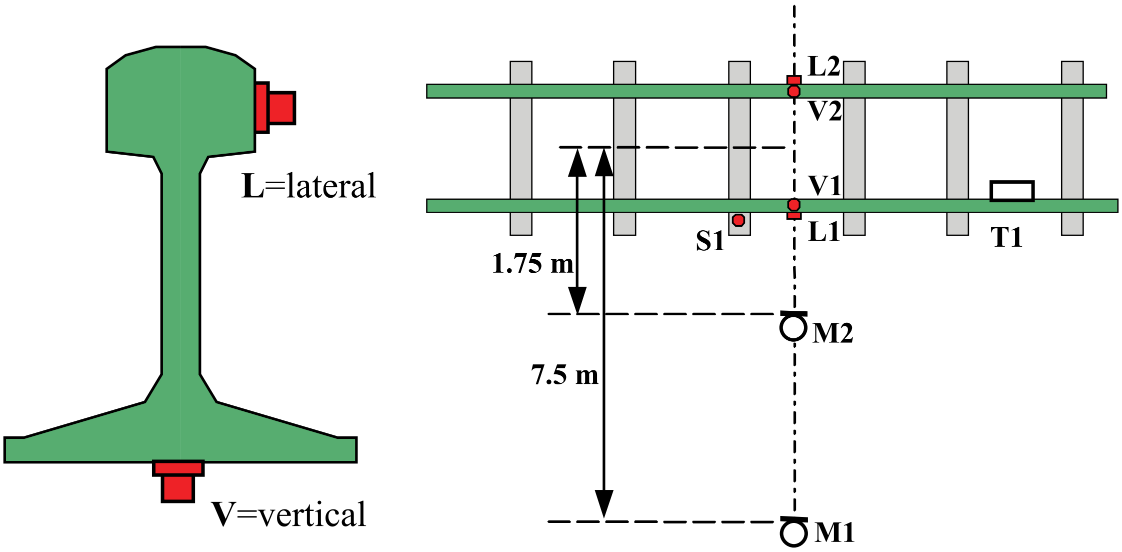

Figure 1: Measurement set-up for VTN (after [4]).

3.2 Data format

The STAIRRS measurement protocol prescribes a specific data format of the signals:

- All signals are transferred to ascii or mat-file format (MATLAB®), each mat-file containing at least the following two variables: scalar **dt** for sample rate (unit [1/s]) and column vector **data** for the time-signal specified by the filename (unit [Pa], [m/s^2] or [-] respectively);
- All signals of one pass-by are equal length and have equal sample rate.
- Each pass-by yields a set of (maximum) 8 mat-files, one for each signal. Any missing signal is provided as a fake signal with zeros as data;

- The 8 files of pass-by number 1 are named M1_001.mat to T1_001.mat. The files for pass-by number 2 are called M1_002.mat to T1_002.mat, and so on.

3.3 Additional parameters

The STAIRRS measurement protocol specifies to make a record of many parameters.
For the application of VTN, only the track and vehicle parameters of Table 2 are of interest.

parameter	current VTN values	usage for VTN
rail type	UIC54, UIC60	optional
track type	ballasted, slab	optional
sleeper type	wood, concrete mono-, biblock	optional
sleeper spacing	free [m]	optional
train speed	free [km/h]	for display only

Table 2: Additional VTN parameters. Optional parameters are required for maximum accuracy.

4. Analysis method

4.1 Formulation

The measurement signals are processed to equivalent one-third octave band spectra, where averaging takes place over pass-by time. The acceleration spectra a_{rms} are integrated to velocity spectra v_{rms} using

$$v_{\mathrm{rms}} = a_{\mathrm{rms}} \; / \, 2\pi f \tag{1}$$

where f represents the frequency.
The algorithm continues with formulations that basically correspond to those used in TWINS. Two line sources are defined for each rail, one for vertical vibrations and one for lateral vibrations. The sound radiated by the lateral line source is considered to possess dipole nature. The web and railhead are responsible for this. The foot of the rail, that radiates the larger part of the vertical vibrations, causes a dipole field as well. However, this dipole field is heavily scattered by ballast and vehicle reflections, and will at some distance resemble a monopole field. The sleepers are also treated as line sources.
Next, a specific acoustic energy per metre of track is admitted to each of these line sources. The sound power W_{source} radiated from each (partial) source equals the acoustic energy produced in each second by a uniformly vibrating plate (effective area A), multiplied by the specific radiation efficiency σ of the source:

$$W_{\mathrm{source}} = \sigma \cdot A \cdot v^2_{\mathrm{rms}} \cdot \rho \cdot c \tag{2}$$

where ρ is the air density and c the speed of sound in air. The radiation efficiency for the sleepers is essentially that of baffled plate:

$$\sigma = \frac{1}{1+\left(\frac{f_{cs}}{f}\right)^2} \tag{3}$$

with critical frequency $f_{cs} = \frac{c}{\sqrt{2\pi w l}}$, where w is the width and l is the length of the source.
The radiation efficiency spectrum of the rails is obtained numerically for an infinite vibrating beam. [8]. The source power being evaluated now, the sound pressure at a certain distance

from the track can be calculated. For line sources in free field conditions, the following applies:

$$p^2_{\mathrm{rms}} = (W \cdot \rho \cdot c \,/\, 2\pi d\,) \cdot Q_\vartheta \qquad (4)$$

where d is the distance from source to receiver, and Q_ϑ is a directivity factor. $Q_\vartheta = 1$ for monopoles en $Q_\vartheta = 2\cos^2(\vartheta)$ voor dipoles; ϑ is the receiver angle relative to the horizontal.

4.2 Ground reflections

The free field conditions are hardly satisfied in practice. Ballast and vehicle will act as partly reflective surfaces. A bit further away from the sources (between microphone positions M2 and M1), different ground conditions may occur at different measurement sites, e.g. an inspection path, type of soil, et cetera. Generally speaking, the influence of reflections is regarded constant between measurement sites, as long as the measurement location and set-up obeys certain rules: the standard for type testing of railbound vehicles [6] restricts height variations to 1 m, excludes sites with reflective objects, while no (other) track should lie between the receiver and source.

VTN assumes free field for the first (nearer) line source. Reflections via ballast and vehicle (and vice versa) are assumed for the second line source. The transfer functions for these reflections incorporates the absorption spectrum of the ballast. Alternatively, the transfer function may be assessed by measurement by using the difference between noise spectrum M1 and M2.

4.3 Track and vehicle noise

Now the track contribution at 7.5 m has been calculated, the vehicle contribution is assessed by subtracting the track noise spectrum from the total noise spectrum (from M1). This approach is particularly sensitive for small errors or bias in the calculation of the track noise. Especially in the frequency band where the track is the pre-dominant source, i.e. below 1.6 kHz, the vehicle contribution is assessed inaccurately.

The measured total noise spectrum is decisive in cases where the calculated track noise exceeds it. If it occurs that the track result is higher than the measured noise in a certain frequency band, the track and vehicle results are respectively set 0.3 dB and 12.0 dB below the measured noise level. With such values, the total level in that frequency band is not affected, while the effect on the *overall* vehicle and track contributions (all frequency bands summed) is negligible.

4.4 Validation

The method and software have been tested in a dedicated measurement campaign in STAIRRS in 2001. A test train was measured at three locations with different track superstructure. The train consisted of freight wagons and passenger coaches. The validation process for VTN focussed on the following aspects:

- Consistent results for different pass-bys, for each vehicle type and for each site.
- The track noise should not be biased (it should always be lower than the measured total noise).
- Ratio of track and vehicle contributions in comparison with three other separation methods, being TWINS [2], PBA [8] en MISO [9].

STAIRRS report [7] gives a detailed discussion of the validation process and the results. Here, we restrict ourselves to summarising the findings:

- VTN calculates the overall track contribution within ±1.5 dB(A).

- The more silent the vehicle, the more inaccurate the overall vehicle contribution.
- If the overall vehicle contribution is higher than the track (according to VTN), its accuracy is best, though in no event better than ±2 dB(A).

Recently, a comparison has been conducted between TWINS model calculations and VTN measurements in the Netherlands. Figure 2 clearly demonstrates the resemblance between the VTN separation results and the TWINS calculations for freight trains and NS passenger trains (Dutch IRM intercity), both on the same measurement site (ballasted track). The differences between VTN and TWINS are in the frequency region of interest smaller than 3 dB in each one-third octave band, except for the vehicle contribution below 2 kHz, where the track is the dominant source.

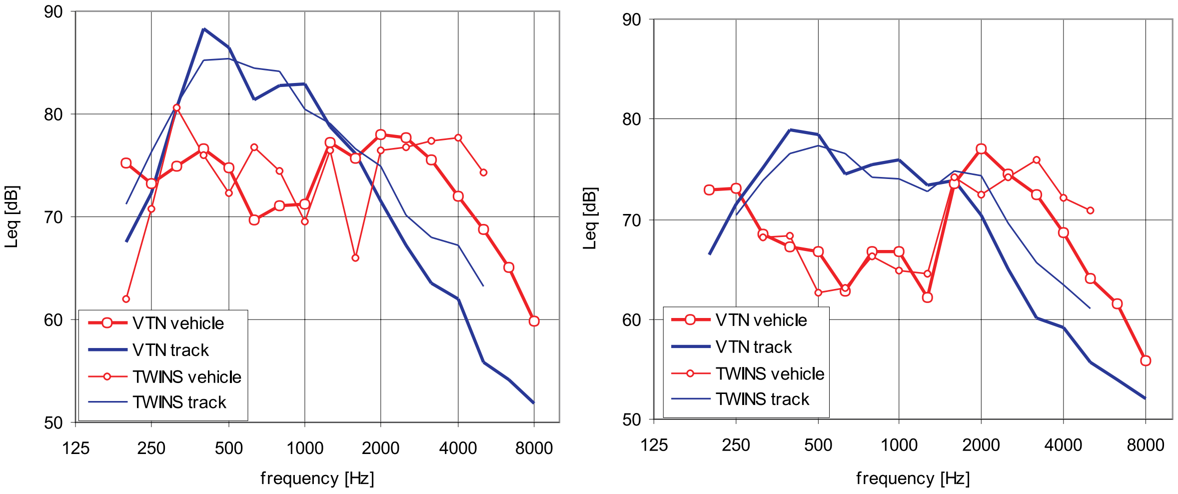

Figure 2: Comparison between VTN and TWINS results. Left: freight train. Right: passenger train.

5. Applications

5.1 Various applications

When, probably in the near future, separate noise contributions from train and track will become of interest, VTN is a tool supporting:

- acceptance testing;
- limit conformance testing.

At the moment, policy makers already request for application in the following cases:

- assessment of noise control measures;
- collection of emission data and monitoring.

Situations where VTN can be applied immediately are:

- ballasted track;
- railway and tramway vehicles;
- rails or wheels with dampers.

Furthermore, it is obvious that traction noise, braking noise and aerodynamic noise are automatically attributed by VTN to the vehicle, and the method can be used at any train speed. The method cannot directly be applied in situations with low barriers, typically lower than 1 m and placed close to the track, because the propagation transfer function needs adjustment, then.

5.2 Potentials in noise control assessment

VTN has proved to be a valuable tool in the assessment of noise reduction measures. Its strength lies in visualising the extent to which a measure acts on either the vehicle emission or the track emission. If the effect on the total noise is smaller than 2 dB(A), studying the VTN results can point out whether the effect is real, i.e. can certainly be attributed to noise measure. The required number of pass-bys of test trains can be reduced considerably if VTN is used to analyse the effect. Thus, the application of VTN can help to economise test campaigns.

The strength of VTN is demonstrated here for two noise control measures: rail dampers and wheel dampers. Figure 3 (left graph) shows the total noise spectra measured at two sites of a ballasted track. One site was equipped with tuned rail dampers (so-called OFWHAT dampers). The test-train runs first over the damped site, then over the reference site, some 50 m away. The spectrum shown is the L_{eq} of two similar vehicles from a run at 120 km/h of that train. Below 2 kHz, some clear differences can be observed. Is the lower level at 1 kHz caused by the rail damper? The answer is given to the right. It shows the result of VTN-analysis of the same measurement. By comparing first the track noise spectra of both situations, it can be seen that the reduction around 1 kHz is mainly due to lower track vibrations, and is in fact wider than one octave. Next, the vehicle contributions are compared. In the frequency range where VTN is accurate (usually above 1.6 kHz), the vehicle contributions are identical between both sites. Below 1.6 kHz, the vehicle results must be treated carefully. Obviously, the peak at 800 Hz on the reference site is not real.

It can be concluded that the rail damper is active in the frequency range between 500 and 2000 Hz. Though at the lower end of this range a slight increase in track noise emission is revealed, the nett effect is a noise *reduction*. The track noise is reduced by 2.0 dB(A), while the total noise reduction is 1.0 dB(A). It can also be concluded that, in order to obtain a higher noise reduction, a stronger damping between 500 Hz and 1 kHz is to be aimed at, rather than damping the rail above this frequency range (as it does now).

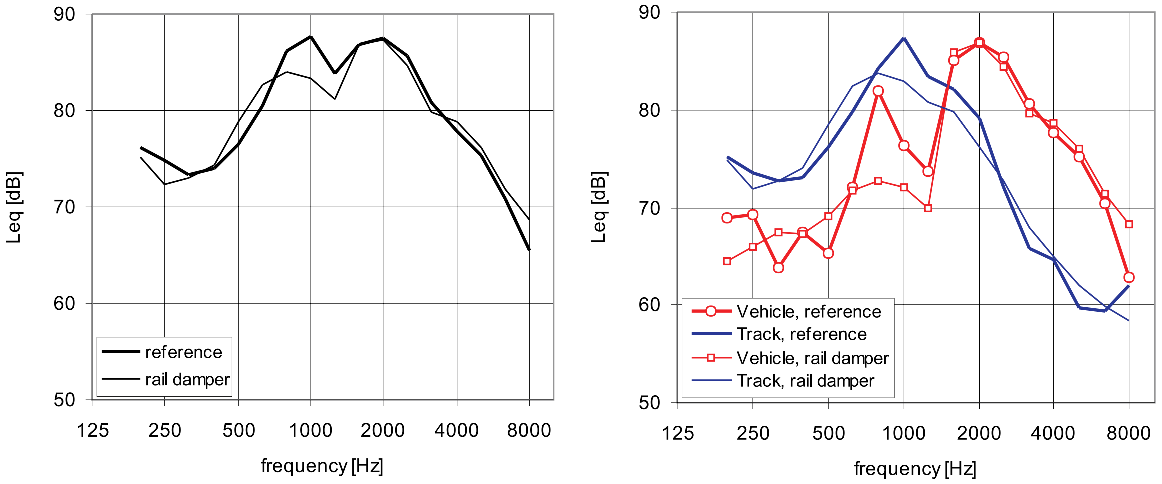

Figure 3: Effect of *rail* damper. Left: total noise, with and without *rail* damper. Right: VTN separation results for both situations.

Another example is given here of a comparison between a test train with and without wheel dampers (Rafil dampers), running on the same type of track as before. Generally it is assumed that the train is dominant at high frequencies. Therefore, wheel dampers are most effective in case they are tuned at high frequencies. But, in which frequency range is the wheel dominant over the track? How big is this dominance?

Observing the left-hand graph of Figure 4, showing the total (measured) noise, it can be expected that achieving a large reduction at 1600 Hz and 2000 Hz by use of a better damper is possible, but VTN analysis shows what cannot be seen by the microphone: the track contribution is still very close to that of the wheel. It appears also that the peak at 1250 Hz is not due to the rail, but to the wheel. Furthermore, VTN shows that at 2500 Hz the wheel has the largest noise dominance. Differences seen at low frequencies could be attributed to small differences in wheel roughness, since neither track nor any other system parameters are changed. VTN has thus allowed better descriptions of those frequencies where the damper performance should be improved and where there is no need of a better improvement, because of track dominance.

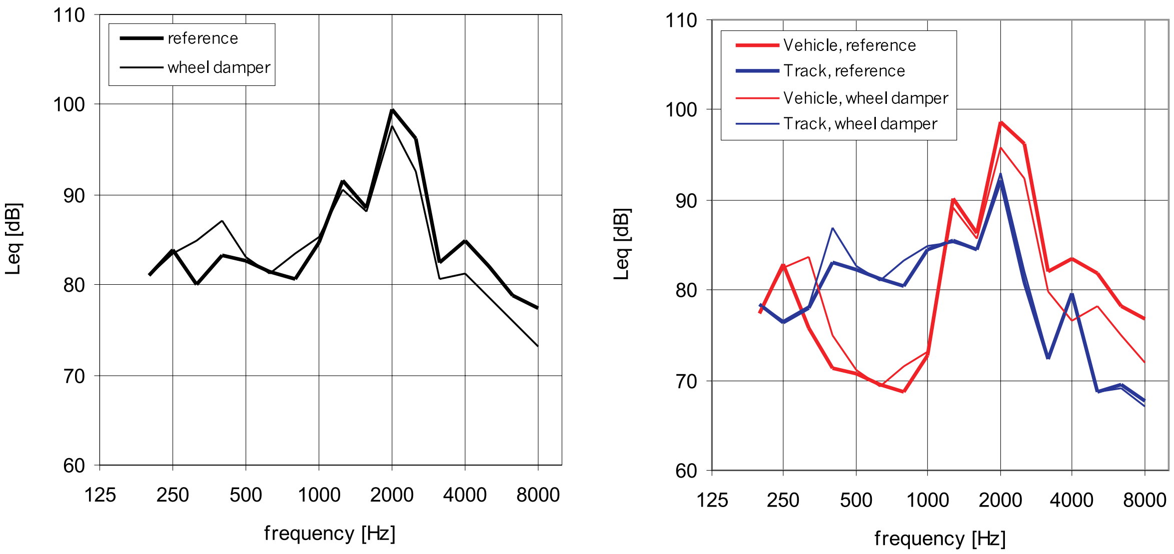

Figure 4: Effect of *wheel* damper. Left: total noise, with and without *wheel* damper. Right: VTN separation results for both situations.

Conclusion

The Vibro-acousticTrack Noise method is a convenient technique to separate the track and vehicle contributions from the pass-by noise of trains. VTN uses a small number of acceleration signals from rails and sleepers, as well as noise signals measured at 7.5 m from the track.

The method is implemented in user-friendly PC software and has proved its strength in the selection of source measures. In the near future, it will be useful for responsibility attribution for the track noise and the vehicle noise to the track manager and the train operator, respectively.

Acknowledgements

The Vibro-acoustic Track Noise method has been developed by AEAT in the European STAIRRS project. Authors are grateful to their former colleague Peter van Tol, now working at HITT (Apeldoorn), for the raw idea that eventually lead to VTN. The ProRail organisation (Utrecht) is acknowledged for their permission to use the TWINS calculations and VTN measurement results shown in Figure 2.

Literature

[1] The STAIRRS project has been presented at several congresses, e.g. INTERNOISE 2001 (The Hague), INTERNOISE 2002 (Dearborn, Michigan), EURONOISE 2003 (Naples), Railtech 2003 (Utrecht).

[2] D.J. Thompson, B. Hemsworth, N. Vincent, Experimental validation of the TWINS prediction program for rolling noise, part 1: description of the model and method, Journal of Sound and Vibration, 1996 (193), pp.123-135.

[3] B. Barsikow, Bestimmung und Analyse des Geräuschs von Güterwagen auf dem Streckennetz der Niederländischen Staatsbahn, raport 95/7, Akustik-Data, 1996, Berlin.

[4] E. Verheijen e.a., STAIRRS deliverable D11 Part 7, Measurement Protocol, Excel Form and Vehicle Label, AEA Technology Rail BV, STR23TR130902AEA3, September 2002.

[5] D.J. Thompson, Comparison of 2D and 3D rail radiation models, Silent Track Technical Document, 80213/2/ISVR/T/rl_radn.doc, August 1999.

[6] prEN ISO 3095, Measurement of noise emitted by railbound vehicles, 2001.

[7] E. Verheijen e.a., STAIRRS Deliverable 11, Part 4 Direct roughness measurements and Vibro-acoustic Track Noise method, AEA Technology Rail BV, STR23TR130902AEA1, September 2002.

[8] M.G. Dittrich, F.G. de Beer, W.J. van Vliet, H.W. Jansen, Acoustical characterisation of rail vehicles and tracks, Proceedings Railtech Conference, Utrecht, April 2003.

[9] F. Létourneaux e.a., Environmental railway noise: a source separation measurement method for noise emissions of vehicle and track, Proceedings of Forum Acousticum Sevilla, November 2002.