Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

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Work Package 6
IMAGINE railway noise source model, default source data and measurement protocol

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1 Introduction

This document provides a joint description of the IMAGINE/Harmonoise model for railway noise sources, including the source models, the measurement protocol and default source data. It is based on earlier work in the Harmonoise project which has been improved on and detailed in the IMAGINE project. The purpose of this document is to provide a concise formulation of the models, methods and default data, to make it accessible for future users.

The models and default data are based on the best available information from different sources, including the Dutch SRM prediction model, which is used as the EU Interim method for railway noise. Whereas the Interim methods are based on the Dutch source data for a particular set of rolling stock and tracks, the IMAGINE model is designed to facilitate the creation of source data for any railway, based on measurements or existing defaults. It should be noted that when the model and default data are applied to a particular railway network, there may be particular types of track, rolling stock or operating conditions which required new measurements to obtain representative source data.

The flowcharts below illustrate where the source models, measurement methods and default data fit in to the overall process of rail traffic noise prediction for a given location. Figure 1 shows the steps required to obtain source emission data for a particular vehicle type using emission models with input data obtained either from measurements or existing default source data. The input source data is given in terms of each physical source, so for rolling noise, traction noise, and others. The emission data for the vehicle type is the combination of this source data.

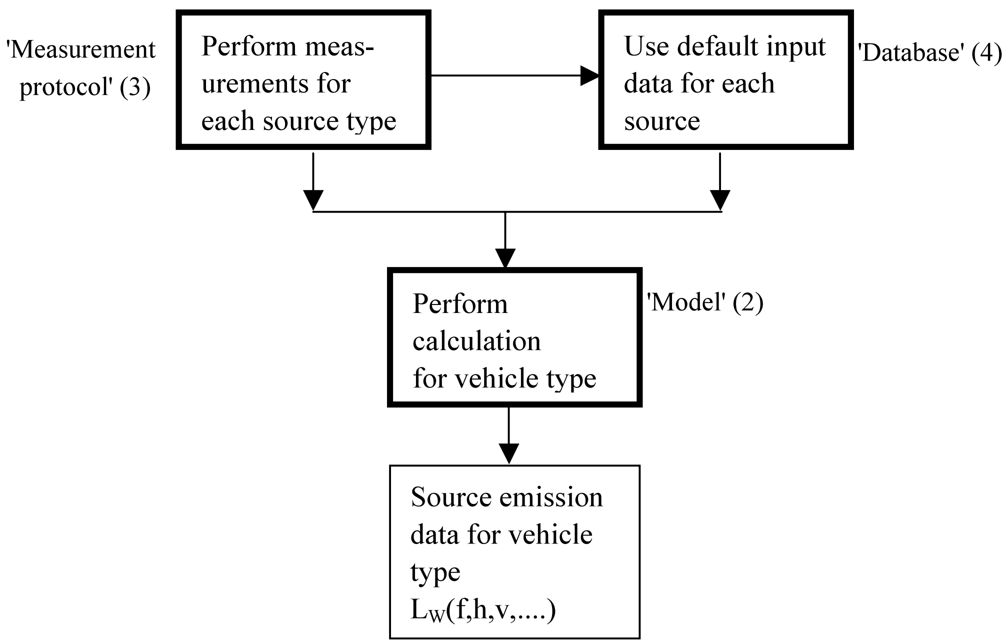


***Figure 1**: Flowchart for determining source emission for a given vehicle type*

The source emission data for each vehicle type is used as input for the traffic noise calculation at any given location along the railway, as shown in figure 2. This report deals primarily with the determination of source emission data for a vehicle type, i.e. the source models, measurement methods and default source input data as shown in figure 1.

Source emission measurements are only required once for a particular vehicle type. Default source data allows the estimation the vehicle emission without measurements, if necessary.

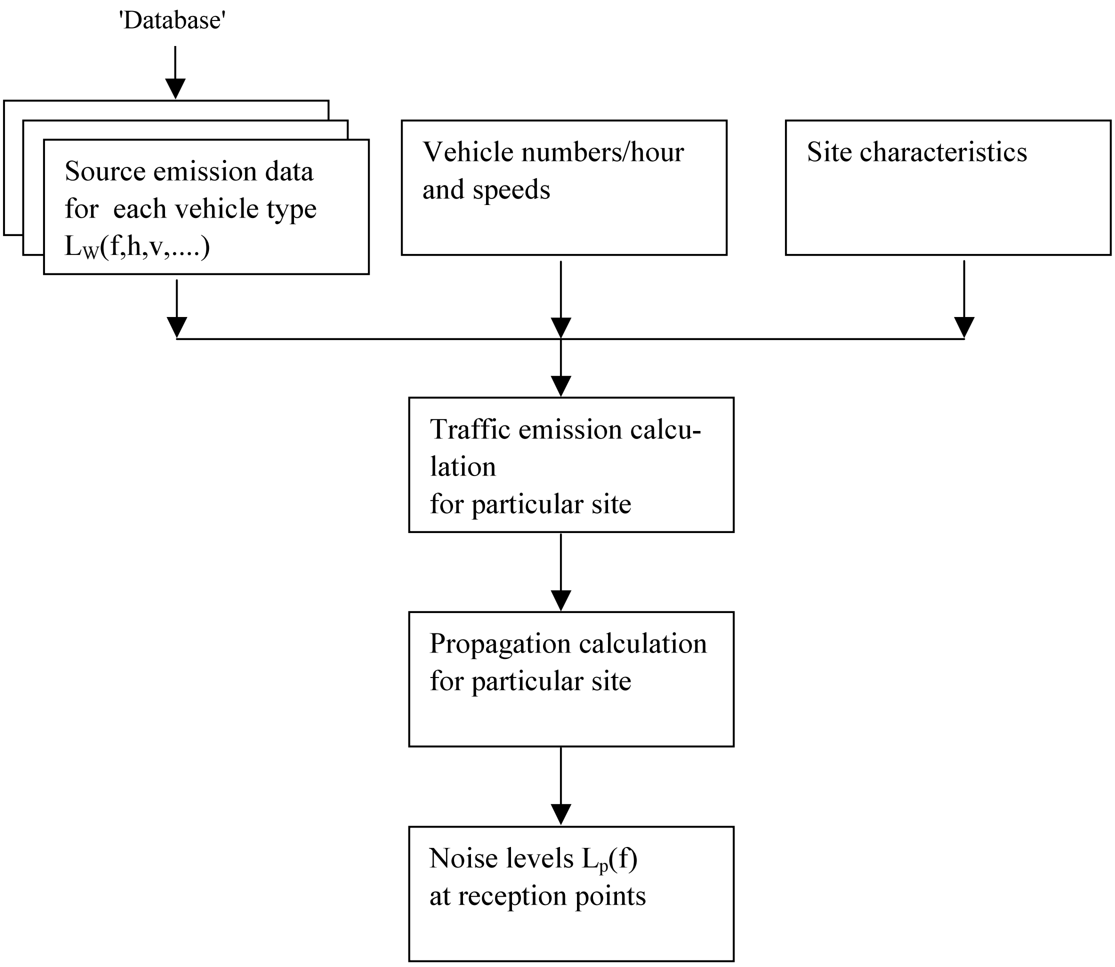


***Figure 2**: Flowchart for determining noise reception levels from vehicle source emission, data, train speeds and composition, site characteristics and propagation.*

2 Source model

2.1 Traffic noise model

The railway traffic noise model calculates an average sound pressure level at a reception point due to contributions from multiple track segments, source heights, vehicle types and speeds, operating conditions and physical sources. The model works with one-third octave band data.
The A-weighted sound pressure level at the receiver position $L_{pAeq,rec}$ due to the traffic flow is determined from energy summation over frequency bands, track segments and source heights:

$$L_{pAeq,rec} = \sum_{i=1}^{B}\sum_{j=1}^{J}\sum_{h=1}^{Nh} \oplus L_{peq,ijh} + L_{FA,i} \tag{1}$$

with
$\Sigma\oplus$ = energy sum: $\Sigma\oplus x_i = 10 \lg (10^{x1/10} + 10^{x2/10} + \ldots)$
$L_{peq,ijh}$ = sound pressure level in frequency band i due to the contribution from segment j and source height h [dB];
$L_{FA,i}$ = A-weighting filter for each frequency band i [dB];
B = number of frequency bands; i = frequency band number;
J = number of segments; j=segment number;
N_h = number of source points (heights); h = source height index.

The sound pressure level $L_{peq,ijh}$ is determined from the level of sound power per unit length in each segment $L_{W,ijh}{}'$ due to the traffic flow (see figure 3) with

$$L_{peq,ijh} = L_{W,ijh}{}' + 10 \lg l_{seg} - A_{total,i} \tag{2}$$

where
$L_{W,ijh}{}'$ is the level of sound power per unit length in frequency band i on segment j and at source height h [dB];
l_{seg} is the segment length [m];
$A_{total,i}$ is the total attenuation due to geometrical spreading, atmospheric absorption, ground reflections, diffraction effects, reflection and scattering [dB].

Expressions for all the attenuation parameters are given in [10].
Five source heights (h) are used to which sound power is allocated (see figure 4).

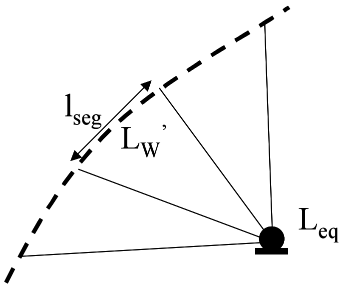


Figure 3: *Sound pressure reception L_{eq} from one segment of track with a sound power per unit length L_W'.*

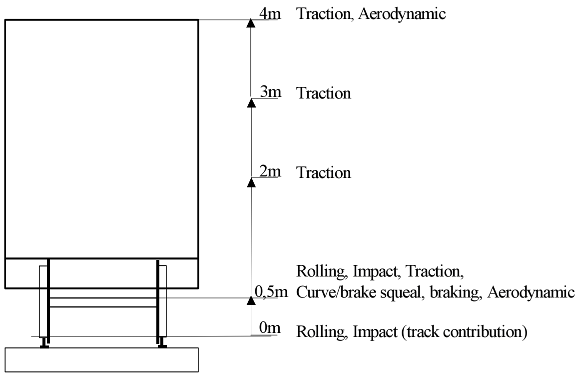


Figure 4*: Main source heights and types*

Table 1*: Railway noise operating conditions and occurrence of physical sources*

Condition	Rolling and impact noise	Traction noise	Braking noise	Curve squeal	Aerodynamic noise
Constant speed	x	x	(x)	x	x
Braking	x	x	x	x	x
Accelerating	x	x		x	x
Curving	x	x	x	x	x
Stationary/idling		x			

The level of sound power per unit length $L_{W,ijh}'$ for the traffic flow depends on the vehicle emission $L_{W\,kmpijh}'$ consisting of contributions from all vehicle types and speeds (*m*) under all relevant conditions (*k*) such as constant speed, braking, accelerating and curving, and each physical source type (*p*). It also takes into account the number of vehicle units (wagons) per hour $N_{u,mk}$ and their length $l_{u,m}$, resulting in an adjustment in the sound power for the proportion of time that vehicles are passing:

$$L'_{W,ijh} = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{p=1}^{P} \oplus \left(L_{W}{'}_{kmpijh} + 10lg\left(\frac{N_{u,mk} l_{u,m}}{1000 v_{mk}}\right) + C_{dir,pih} \right) \tag{3}$$

with

K = number of operating conditions relevant at the segment:

k: 1 =constant speed, 2 = braking, 3 = accelerating, 4= curving; 5= stationary;

M = total number of vehicle types and speeds;

m =index for vehicle type and speed;

P = number of physical source types:

p: 1=rolling noise and impact, 2=traction noise, 3= aerodynamic noise, 4 = braking noise, 5 = curve squeal;

$N_{u,mk}$ = number of units of type and speed m and condition k, per hour;

$l_{u,m}$ = length of units of type m in meters;

v_{mk} = train speed in km/h, for type m and condition k;

$C_{dir,pih}$ = directivity function for each source type p, source height h and frequency band i.

Directivity C_{dir} is in the horizontal plane and by default is assumed a dipole, given by:

$$C_{dir,pih} = 10\ lg(2\ cos^2(\pi/2-\varphi)) \tag{4}$$

where φ is the angle in the horizontal plane between the propagation path and the source segment.

The source strength is expressed in terms of sound power per unit length as this is independent of train length, and for a given type of train the number of units may vary. Equivalent point source strength can be derived for the traffic flow using $L_W{'}_{ijh} + 10\ lg\ l_{seg}$, and for an individual train or vehicle using $L_W{'}_{kmpijh} + 10\ lg\ l_{veh}$.

It should be noted that each operating condition can potentially include several physical sources, as shown in table 1. In practice, only one or a few physical sources will be dominant for a given operating condition, but it should be taken into account that there will often be a mix of sources present. Some sources may dominate a particular frequency range. For example, during curving or passing a set of points, rolling noise, impact noise, traction noise and curve squeal can occur together; curve squeal will often dominate the high frequency range above 1 kHz; traction, rolling and impact noise could dominate the low and medium frequency range.

2.2 Sound power from pass-by sound pressure

The source model includes all those physical sources that may potentially dominate the average noise level for particular locations or operating conditions. Discrete source heights used in the model are 0m, 0.5m, 2m, 3m and 4m above the rail surface, as illustrated in figure 2. Each physical source has one or more common source heights. As many of the basic source data are obtained from measurements of a single train pass-by, it is easier to define the source calculations from sound pressures at a fixed distance (7.5m).

For a given train type m, operating condition k and source height h, the relation between level of sound power per unit length and sound pressure level $L_{peq,Tp,kmih}$ at 7.5 meters during pass-by transit time

$T_p = l_{veh}/v$ and for test vehicle length l_{veh} is given by:

$$L_W{}'_{kmih} = L_{peq,Tp,kmih} + 10lg(2\pi r) - A_{excess,i} - 10lg(atan(\frac{lveh}{2r})) \quad (5)$$

where $A_{excess,i}$ is the total attenuation averaged over the whole view angle, excluding geometrical spreading, and r is the distance to the track centreline. For each source type the expressions are given as sound pressure levels at 7.5m. The sound power terms required for formula (3) can now be obtained for each physical source and source height, converting with formula (5). Where available, currently proposed default values are given for each source type.

The sound power or the sound power per unit vehicle length is a useful quantity for input to the further calculation process. It can be written in this way for both individual sources and source heights.

This expression is already useful for whole train or vehicle measurements if partial sources and individual parametric effects such as roughness or operating conditions are not included.

In the following sections, the models for partial sources are written in terms of sound pressure, as this is most practical to measure.

2.3 Source model

Calculation models for each source type are given in the following. An overview is given in table 2.

***Table 2**: Calculation models for physical railway noise sources*

Source type	**Typical source heights**	**Formula** (refer to text for further details)
Rolling noise See 2.3.1	0m 0.5m	$L_{peqi,roll}\ (h{=}0m){=}L_{rtot,net,i}\ (v)\ +\ L_{Hpr,nl,tr,i}\ +\ 10\ lg\ (N_{ax}/l_{veh})$ $L_{peqi,roll}(h{=}0{,}5m){=}L_{rtot,net,I}\ (v)\ +\ L_{Hpr,nl,veh,i}\ +\ 10\ lg\ (N_{ax}/l_{veh})$
Impact noise See 2.3.1	0m, 0.5m	$L_{rtot}(\lambda)\ =\ L_{rveh}(\lambda)\oplus L_{rtr}(\lambda)\oplus L_{rimpact}(\lambda)$ further as rolling noise
Traction noise, total, see 2.3.2	0.5m, 2m, 3m, 4m	$L_{peq,i,traction,idle}$,$L_{peq,i,traction,acc}$, $L_{peq,i,\ traction,cs}$, *and* $L_{peq,i,\ traction,dec}$ *or:* $L_{ptraction,i}(\ n_{drive}\ ,\ n_{fan})\ =\ L_{pdrive,i}(n_{drive})\oplus L_{pfan,i}(n_{fan})\oplus L_{pdj,i}$
Traction noise, drive, see 2.3.2	0.5m, 2m, 3m, 4m	$L_{pdrive,i}(n_{drive})\ =$ $L_{pdrive,nmax,i}(f_i\ .(n_{drive,max}/n_{drive})\ )\ +\ C_{drive}\ \lg\ (n_{drive}/n_{drive,max})$
Traction noise, fan, see 2.3.2	0.5m, 2m, 3m, 4m	$L_{pfan,i}(n_{fan})\ =$ $L_{pfan,nmax,i}(f_i\ .(n_{fan,max}/n_{fan}\ )\ )\ +\ C_{fan}\ \lg\ (n_{fan}/n_{fan,max})$
Traction noise, other, see 2.3.2	0.5m, 2m, 3m, 4m	$L_{pdj,i}\ =\ L_{pi}(f){+}\ 10\ \lg\ (d_j)$
Deceleration noise, total See 2.3.3	0.5m	$L_{pdeceleration,i}(v)\ =\ L_{pbrake,i}(v)\oplus L_{pdsqueal,i}$
Deceleration noise, braking See 2.3.3	0.5m	$L_{pbrake,i}(v)\ =\ L_{pbrake,i}(v_0)\ \ +\ C_{brake}\ \lg\ (v/v_0)$
Deceleration noise, squeal See 2.3.3	0.5m	$L_{pdsqueal,i}\ =\ L_{psqueal,i}\ \ +\ 10\ \lg\ (d_{squeal})$ below squeal cut-in speed (when mechanical braking starts)
Curve squeal See 2.3.4	0.5m	$L_{psqueal}$ = constant (average value) in curve with d< 1000m
Aerodynamic noise See 2.3.5	0.5m, 2m, 3m, 4m	$L_{paero,h}(f,v)\ =\ L_{paero,h}(f,v_0)\ +\ \alpha_h(f)lg\ (v/v_0)$

2.3.1 Rolling noise and impact noise

Rolling noise is calculated at axle height and track height, and has as input the total effective roughness $L_{r,tot,i,}(v)$ as function of train speed v, the track and vehicle transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ and the axle density N_{ax}/l_{veh}:

$$L_{peqi,roll}\ (h=0m)=L_{rtot,i}\ (v)\ +\ L_{Hpr,nl,tr,i}\ +\ 10\ lg\ (N_{ax}/l_{veh}) \tag{6}$$

$$L_{peqi,roll}(h=0{,}5m)=L_{rtot,i}\ (v)\ +\ L_{Hpr,nl,veh,i}\ +\ 10\ lg\ (N_{ax}/l_{veh}) \tag{7}$$

N_{ax} is the number of axles per vehicle and l_{veh} the vehicle length. The total effective roughness $L_{r,tot,i}$ (for frequency band i) is the unfiltered effective wheel-rail roughness, which can be derived from rail vibration measurements or from direct roughness measurement on wheels and rails and a contact patch filter. If the roughness is obtained as a function of wavelength λ, it must be converted to the required speed using the relation $\lambda = v/f$, where f is frequency [Hz] and v is train speed in [m/s].

The transfer functions $L_{Hpr,nl,tr,i}$ and $L_{Hpr,nl,veh,i}$ are speed independent and can be determined either by calculation or by measurement. They have the reference unit of sound pressure squared per unit roughness squared, normalised to the axle density N_{ax}/l_{veh}. They are known from measurement or calculation for different track and vehicle types and are defined by

$$\begin{aligned} L_{Hpr,nl,tr,i} &= L_{peq,tr,i}(v) - L_{rtot,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \\ L_{Hpr,nl,veh,i} &= L_{peq,veh,i}(v) - L_{rtot,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \end{aligned} \tag{8}$$

where $L_{peq,veh,i}(v)$ and $L_{peq,tr,i}(v)$ are the vehicle and track noise contributions in the sound pressure level, i is the frequency band number, v is the speed, $L_{rtot,i}(v)$ is the combined effective roughness at speed v.

Rolling noise is speed dependent and is therefore relevant for the operating conditions constant speed, acceleration, deceleration and curving.

It is practical to work with effective roughness as it is easy to measure and is related directly to the real excitation. Effective roughness is related to direct roughness via the contact filter $A_3(\lambda)$:

$$L_{rtr}(\lambda) = L_{rtr,dir}(\lambda)\ +\ A_3(\lambda) \tag{9}$$

Combined effective roughness can be obtained from a rail vibration measurement of the vehicle(s) in question, using the formula

$$L_{rtot,i}(v) = L_{veq,i}(v) + 10\lg\left(\frac{D_{s,i}}{8.68 N_{ax}/l_{veh}}\right) - A_{2,i} - 20\lg(2\pi f_i) \tag{10}$$

where $L_{veq,i}(v)$ is the equivalent vertical railhead vibration level during a pass-by, $D_{s,i}$ is the vertical track decay rate in one third octave bands and $A_{2,i}$ is the difference spectrum between de rail displacement in the contact point and the effective roughness. $A_{2,i}$ is tabulated (see appendix) but can also be calculated using TWINS. Spatial decay $D_{s,i}$ can be determined from pass-by measurement (e.g. PBA) or from hammer impact response measurements (see Conventional Rail TSI).

The total (combined vehicle and track) transfer function can be obtained from the sound pressure level and effective roughness, whereby separation into track and vehicle contributions can be done in several ways:

- using a reference vehicle (see [2])
- by other separation techniques
- by using a default distribution function (see appendix)
- by calculation methods such as TWINS.

For a given network or known test site, the track transfer function might only have to be measured once or occasionally, after which it is well known or even tabulated. It should be speed independent.

The track transfer function can also be used in the same way for bridge noise. For steel bridges it will tend to be significantly higher than for normal tracks. Bridge noise is included in the rolling noise source by using a track transfer function at h=0m including the track and the bridge.

Impact noise can be caused by rail joints, crossings and points. It can vary in magnitude and can dominate over rolling noise. As it is often localised, it has to be taken into account when choosing track segmentation.

If present, impact noise is included in the rolling noise term by (energy) adding a supplemental roughness to the effective combined roughness:

$$L_{rtot}(\lambda) = L_{rveh}(\lambda) \oplus L_{rtr}(\lambda) \oplus L_{rimpact}(\lambda) \qquad (11)$$

This approach is partly based on [18].
Impact noise will depend on the severity and number of impacts per unit length or joint density n_l, so the impact roughness can be given as

$$L_{rimpact}(\lambda) = L_{rimpact,nl}(\lambda) + 10\ lg(n_l/0.01) \qquad (12)$$

where $L_{rimpact,nl}(\lambda)$ is the normalised impact roughness level and n_l is the joint density. The default impact roughness is given for a joint density $n_l = 0.01$, which is 1 impact per 100m track.

Situations with different numbers of joints can be approximated by adjusting the joint density n_l.
A different joint severity can be obtained by increasing the impact roughness level by approximately 20 lg h, where h is the joint step height.

It should be noted that when modelling the track layout and segmentation, the rail joint density should be taken into account, i.e. it may be necessary to take a separate source segment for a stretch of track with points.

The track noise $L_{ptr,i}$ is allocated to h=0m, the vehicle noise $L_{pveh,i}$ to h=0,5m.

2.3.2 Traction noise

Traction noise is specified for each characteristic operating condition: idling, acceleration constant speed and deceleration. The source strength at each operating condition is an average for 'normal conditions' and therefore takes an 'average load' into account. This results in the quantities $L_{peq,i,traction,idle}$,$L_{peq,i,traction,acc}$, $L_{peq,i,\ traction,cs}$, and $L_{peq,i,\ traction,dec}$.

These quantities can either be obtained from measurement of all sources at for each operating condition, or the partial sources can be characterised individually, determining their parameter dependency and relative strength. This may be done by means of measurements on a stationary vehicle, varying shaft speeds of the traction equipment.

As far as relevant, several traction noise sources have to be characterised which are not all directly train speed dependent:

- noise from the powertrain, such as diesel engine (including inlet, exhaust and engine block) , gear transmission, electrical generators, mainly dependent on drive rpm, and electrical sources such as converters, which may be mostly load dependent;
- noise from fans and cooling systems, depending on fan rpm; in some cases fans can be directly coupled to the driveline;
- intermittent sources such as compressors, valves and others with a characteristic duration of operation and corresponding duty cycle correction for the noise emission.

As each of these sources can behave differently at each operating condition, the traction noise must be specified accordingly. The source strength is obtained from measurement under controlled conditions. In general, locomotives will tend to show more variation in loading as the number of vehicles hauled and thereby the power output can vary significantly, whereas fixed train formations such as EMUs, DMUs and high speed trains have a more well defined load. More details on traction noise can be found in [3,11,13]. Traction noise is the energy sum of noise due to the powertrain L_{pdrive}, cooling fans L_{pfan} and other (intermittent) sources L_{pd}:

$$L_{peqi,traction} = L_{pdrive,i} \oplus L_{pfan,i} \oplus L_{pd,i} \tag{13}$$

where
$\Sigma\oplus$ = energy sum: $\Sigma\oplus x_i = 10 \lg (10^{x1/10} + 10^{x2/10} + \ldots)$

Noise from the powertrain is often approximately proportional to the driveshaft speed n_{drive} of the diesel engine or electric motor with gear transmission. For electrically powered vehicles, the shaft speed of the electric motor(s) and gear transmission is often directly linked to the train speed. For diesel-powered vehicles however, the engine shaft speed is often independent from the train speed, and varies with required power. Some vehicles also have fixed speed diesel engines. Many modern electric locomotives, EMUs and high speed train units have electrical power control systems that emit varying tonal noise which increases with power output and is especially audible during high torque conditions. In these cases where power output or torque is the main influence parameter, noise levels for each characteristic operating condition are required. For locomotives, it is important to apply a sufficiently high load to obtain realistic noise emission levels. A hauled load of at least 5 times the locomotive weight is recommended.

For those vehicles for which the noise emission depends strongly on driveshaft speed, the following formula can be used to estimate noise emission at various operating conditions:

$$L_{pdrive,i}(n_{drive}) = L_{pdrive,nmax,i}(f_i \cdot (n_{drive,max}/n_{drive})) + C_{drive}\ lg\ (n_{drive}/n_{drive,max}) \tag{14}$$

The noise level at maximum shaft speed $L_{pdrive,i,nmax}$ is determined for a maximum drive speed $n_{drive,max}$ (or the nearest feasible speed) and the factor C_{drive} is determined from 2 or more operating points. A default value for C_{drive} is 30, if mechanical sources are predominant. The noise level for arbitrary speed is determined from a level shift (C_{drive} term) and a frequency shift $(n_{drive,max}/n_{drive})$.

For fan noise with variable shaft speed n_{fan}, the fan noise L_{pfan} is given in a similar manner:

$$L_{pfan,i}(n_{fan}) = L_{pfan,nmax,i}(f_i \cdot (n_{fan,max}/n_{fan}\ )\ ) + C_{fan}\ lg\ (n_{fan}/n_{fan,max}) \tag{15}$$

$L_{pfan,nmax}$ is determined for a maximum drive speed $n_{fan,max}$ (or the nearest feasible speed) and the factor C_{fan} is determined from 2 or more operating points. A default value for C_{fan} is 50, if flow noise sources are predominant. If the fan has fixed settings such as high and low speed, or is automatically controlled, the noise level that is characteristic of each operating condition is required. If cooling fans are attached to the driveshaft linked to the axles, then it is possible that fan noise may dominate drive noise at higher speeds. In this case formula (15) may coincide with formula (4), with C_{drive}=C_{fan}.

For any other traction or auxiliary sources q with non-continuous or intermittent operation the level L_{pqdi} corrected for the duty factor d_q (proportion of operating time to total time) is determined with:

$$L_{pdqi} = L_{pq,i} + 10\ \lg\ (d_q) \tag{16}$$

The operational level $L_{pq,i}$ is obtained from measurement of source q; the duty factor is determined from the percentage of time the source is active. If the corrected level is significantly lower than other traction noise from the powertrain or cooling system, it can be omitted. Such souces may also only be significant during idling or at low speeds, and for a short duration.

For diesel drive noise and for fan noise, defaults for shaft speeds can be given for each operating condition, as shown in table 3.

Table 3: *Default drive shaft speeds for diesel engines and fan shaft speeds for different operating conditions*

Drive speed (diesel engine) n_{drive}	Fan speed n_{fan}
Constant speed	
$n_{driveidle} + 0.5(n_{drivemax} - n_{driveidle})$	$n_{fanmin} + 0.25(n_{fanmax} - n_{nfanmin})$ or n_{fanLOW}
Acceleration	
$n_{driveidle} + 0.75(n_{drivemax} - n_{driveidle})$	$n_{fanmin} + 0.75(n_{fanmax} - n_{nfanmin})$ or $n_{fanHIGH}$
Deceleration	
$n_{driveidle}$	$n_{fanmin} + 0.75(n_{fanmax} - n_{nfanmin})$ or $n_{fanHIGH}$
Idling	
$n_{driveidle}$	n_{fanmin} or n_{fanLOW}

If it is possible to measure traction noise for all required conditions with all relevant sources in operation, then formulas (13)-(15) can be omitted. In that case, source spectra are determined for idling $L_{peq,idle}$, acceleration $L_{peq,acc}$, constant speed, $L_{peq,cs}$, and deceleration $L_{peq,dec}$. Measurements on locomotives should be performed with a load of at least 5 times the vehicle weight to ensure sufficient power output.

The source heights for traction noise sources are determined either by the physical position of the component concerned, or by measurement using special techniques such as microphone array measurements. Sources such as gear transmissions and electric motors will often be at axle height of 0.5m. Louvers and cooling outlets can be a various heights; engine exhausts are often at roof height of 4m. Other traction sources such as fans or diesel engine blocks may be at 2 or 3 m height. If the exact source height is in between the model heights, the sound energy is distributed proportionately over the nearest adjacent source heights.

2.3.3 Deceleration noise

Deceleration noise consists of braking noise at normal speeds (often broadband) and brake squeal, which usually sets in at lower speeds. The corresponding sound pressure expressions have to be determined, if applicable:

For braking noise with speed dependency, especially broadband braking noise at speed:

$$L_{pbrake,i}(v) = L_{pbrake,i}(v_0) + C_{brake} \lg (v/v_0) \tag{17}$$

Here, at least two measurements at different speed are required whilst braking; one at reference speed v_0 to determine $L_{pbrake,i}(v_0)$ and another to determine the speed dependency factor $C_{brake.}$

For brake squeal:

$$L_{pdsquea,il} = L_{psqueal,i} + 10 \lg (d_{squeal}) \tag{18}$$

Here the squeal noise level $L_{psqueal,i}$ and its duration correction d_{squeal} need to be measured, and the speeds at which brake squeal occurs.

The energy sum is taken for braking and brake squeal (if relevant) to give the overal deceleration noise sound pressure spectrum as a function of speed.

$$L_{pdeceleration,i}(v) = L_{pbrake,i}(v) \oplus L_{pdsqueal,i} \tag{19}$$

Deceleration noise is normally allocated to the source height 0,5m. If it is well below the rolling noise level at all speeds, it can be neglected.

2.3.4 Curve squeal

Curve squeal is a special source that is only relevant for curves and points and is therefore localised. As it can be significant, an appropriate description is required. Curve squeal is generally dependent on curvature, friction conditions, train speed and track-wheel geometry and dynamics. As all these parameters are rather complex to include in a traffic noise prediction model, it is proposed to use noise levels measured during the transit time of a vehicle squealing in a curve. This should then be corrected for the percentage of pass-bys it is expected to occur, as a default 50%, which reduces the level by 3 dB. This takes all statistical effects into account such as variation in geometry, friction, and humidity. The statistical variations over the length of the vehicle are accounted for by using the equivalent noise level measured over the pass-by length. The emission level to be used should be determined for curves with radius below 1000m and for sharper curves and branch-outs of points with radii below 100m. The noise emission should be specific to each type of rolling stock, as certain wheel types may be significantly less prone to squeal than others. The emission level $L_{p,i,squeal}$ is given as a function of speed and curve radius, depending on the track (curve or points) and the vehicle type. The source height is at axle height (0.5m).

Squeal noise levels for different speeds or curve radii can be approximated by the following relationship, based on [19]:

$$L_{p,squeal,i} = L_{p,squeal,i}(v_0,R_0) + 20 \lg (v/v_0) - 20 \lg (R/R_0) \tag{20}$$

This formula may be used for deriving squeal noise levels at other speeds or radii, but preferably by no more than a factor 10 in speed or radius.

2.3.5 Aerodynamic noise

Aerodynamic noise is only relevant at high speeds and therefore it should first be verified whether it is actually necessary for application purposes. If the rolling noise roughness and transfer functions are known, it can be extrapolated to higher speeds and a comparison can be made with existing high speed data to check whether higher levels are produced by aerodynamic noise. If train speeds on a network are limited to 250 km/h, in some cases aerodynamic may not be necessary to include, depending on vehicle design.

The aerodynamic noise contribution is given as a function of speed and source height:

$$L_{paero,i}(h,v) = L_{paero,i}(h,v_0) + \alpha_i(h) lg\ (v/v_0) \tag{21}$$

where v_0 is a speed at which aerodynamic noise is dominant and $\alpha_i(h)$ is a coefficient determined from 2 or more measurement points, for sources at known source heights, for example the first bogie (0.5m) and the pantograph recess heights (4m).

These defaults are intended for trains with unshielded bogies and unshielded pantograph recesses.

3 Default source data

3.1 Overview of default parameters

For all of the physical sources, best known current default values are provided in this section which can be used if no specific measurement data are available. Obviously this may result in prediction errors if there is a large difference with specific emission of particular vehicles or train types. This should be carefully assessed when deciding whether to use default data or to measure particular rolling stock. All of the default values are given in terms of sound pressure level in one-third octave bands at 7.5m during transit time T_p, as this is easy to compare with measurement. The defaults provided are based on best available data and estimates at the time of preparation of this document.

***Table 4**: Overview of proposed default input quantities for the railway noise source model*

Source type	Default quantities	Vehicle	Track
Rolling noise	N_{ax}/l_{veh} =0.15(passenger coach) $L_{Hpr\,nl,i}$ for track $L_{Hpr\,nl,i}$ for vehicle $L_{r,total,i}(v)$ for vehicle/track combinations	Cast-iron tread K-block Disc	Concrete soft pad Concrete stiff pad Wooden sleeper Rail roughness: ISO, TSI, Network average, Corrugated
Impact noise	$L_{rimpact}(\lambda)$ n_{nl} = 1/100 m		Average joints, points and crossings
Traction noise, drive	$L_{p,drive,i}(n_{drive})$ Diesel: $n_{drive} = n_{25\%}, n_{50\%}, n_{75\%}$ Electric: 1 or 2 speeds accelerating at normal load $C_{drive} = 30$	DMU, Dloco EMU, Eloco	
Traction noise, fan	$L_{p,fan,i}(n_{fan})$ $n_{fan} = n_{50\%}$ or n_{low}, n_{max} or n_{high} d_{fan} = 80% for n_{low}, d_{fan} = 20% for n_{high} $C_{fan} = 50$	EMU, Eloco	
Traction noise, other	L_{pi}, d	Compressor and relief valves	
Deceleration noise, braking	$L_{p,brake,i}(v) = 88 + 30 \lg (v/80)$ @800-8000 Hz Only for CI braked vehicles	Cast-iron braked vehicles	
Deceleration noise, squeal	$L_{pbrakesqueal,i}$ = 100 dB @ 1kHz Below 50 km/h	Freight HST, EMU	
Curve squeal	$L_{p,curve\ squeal,\ points,i}$ = 100 dB @ 1kHz, 2kHz $L_{p,curve\ squeal,\ curve,i}$ = 95 dB @ 2kHz , 4kHz	All, unless demonstrated squeal free	Points (when curving) Curve
Aerodynamic noise	$L_{paero,i}(h=0{,}5m) = 63 + 60 \lg(v/80)$ @20-8000Hz $L_{paero,i}(h=4m) = 65 + 60 \lg(v/80)$ @4000-5000Hz	Unshielded bogies and pantograph recesses	

3.2 Defaults for rolling noise

Default data is given for total effective roughness and track and vehicle transfer functions:
Total effective roughness: for cast-iron and composite brake blocked vehicles and for disc-braked vehicles, running on very smooth track or track with medium roughness (average Dutch network).
Vehicle transfer functions: for vehicles with wheels of several diameters.
Track transfer functions: for ballasted tracks with concrete sleepers/stiff pads, concrete sleepers/soft pads, and wooden sleepers.

Direct (unfiltered) rail roughness is given for ISO, TSI+, Dutch average network and corrugated conditions in Appendix D.

Table 5*: Tabulated effective roughness for smooth and average track roughness, and for 3 brake types.*

Wavelength [cm]	CI block braked vehicle on smooth track	Disc braked vehicle on smooth track	Composite block braked vehicle on smooth track	CI block braked vehicle on avg.netw. track	Composite block braked vehicle on avg.netw. track	Disc braked vehicle on avg.netw. track
63,00	21,00	6,00	4,00	21,64	13,51	13,79
50,00	20,00	5,00	3,00	20,64	12,51	12,79
40,00	19,00	4,00	2,00	19,64	11,51	11,79
31,50	18,00	3,00	1,00	18,64	10,51	10,79
25,00	17,00	2,00	0,00	17,64	9,51	9,79
20,00	16,00	1,00	-1,00	16,64	8,51	8,79
16,00	15,00	0,00	-2,00	15,64	7,51	7,79
12,00	14,00	-1,00	-3,00	14,64	6,51	6,79
10,00	14,00	-2,00	-4,00	14,51	5,51	5,79
8,00	13,51	-3,00	-5,00	13,98	4,51	4,79
6,30	14,32	-4,20	-6,20	14,61	3,31	3,59
5,00	13,77	-5,50	-7,50	14,02	2,01	2,29
4,00	12,74	-6,90	-8,90	12,97	0,61	0,89
3,20	11,71	-8,60	-10,60	11,91	-1,09	-0,81
2,50	10,19	-10,50	-12,50	10,37	-2,99	-2,71
2,00	8,18	-12,80	-14,80	8,35	-5,29	-5,01
1,60	2,35	-15,80	-17,80	2,67	-8,29	-8,01
1,20	-2,54	-19,50	-21,50	-2,12	-11,99	-11,71
1,00	-5,00	-23,40	-25,40	-4,70	-15,89	-15,61
0,80	-8,00	-25,60	-27,60	-7,64	-18,09	-17,81
0,63	-10,54	-27,50	-29,50	-10,12	-19,99	-19,71
0,50	-18,06	-29,50	-31,50	-16,73	-21,99	-21,71
0,40	-20,88	-32,00	-34,00	-19,46	-24,49	-24,21
0,32	-23,23	-33,50	-35,50	-21,56	-25,99	-25,71
0,25	-25,84	-35,70	-37,70	-24,03	-28,19	-27,91
0,20	-27,79	-37,60	-39,60	-25,96	-30,09	-29,81
0,16	-29,79	-39,60	-41,60	-27,96	-32,09	-31,81
0,13	-31,79	-41,60	-43,60	-29,96	-34,09	-33,81
0,10	-33,79	-43,60	-45,60	-31,96	-36,09	-35,81

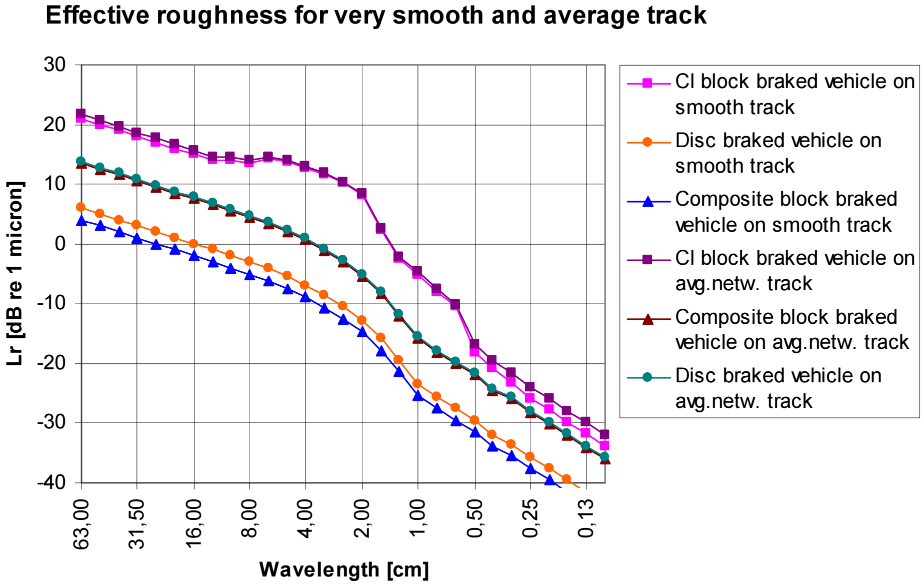


***Figure 5**: Effective roughness for wheels with cast-iron block brakes, disc brakes and composite block brakes. A wavelength of 1 cm corresponds to 2500 Hz at 90 km/h.*

***Table 6**: Tabulated vehicle transfer functions*

	Wheel diameter			
Freq. [Hz]	920 mm	1200 mm	840 mm	640 mm
20	27.0	37.0	22.0	26.0
25	32.0	42.0	27.0	32.0
32	37.0	47.0	32.0	38.0
40	42.0	53.0	37.0	44.0
50	47.4	59.5	43.1	40.6
63	51.9	59.4	48.9	47.2
80	56.5	59.3	54.7	53.7
100	62.4	56.9	63.6	64.1
125	66.9	56.8	69.5	70.7
160	69.3	61.8	70.5	71.3
200	72.5	70.1	70.6	70.4
250	74.8	75.1	71.6	71.0
316	74.7	75.3	72.8	72.9
400	72.8	73.7	73.7	76.0
500	72.7	74.0	74.8	77.8
630	75.3	76.2	76.4	77.4
800	76.7	75.8	75.8	75.2
1000	79.3	78.0	77.4	74.8
1250	84.8	84.9	83.1	77.6
1600	92.4	95.8	90.8	78.9
2000	97.9	102.7	96.4	81.7
2500	100.6	104.1	99.6	87.7
3160	103.8	104.7	103.5	97.1
4000	106.5	106.0	106.6	103.1
5000	107.4	107.2	107.9	107.9
6350	107.9	108.3	108.9	108.9
8000	108.8	109.5	110.2	110.2
10000	109.8	110.6	111.5	111.5
12500	109.8	110.6	111.5	111.5
16000	109.8	110.6	111.5	111.5
20000	109.8	110.6	111.5	111.5

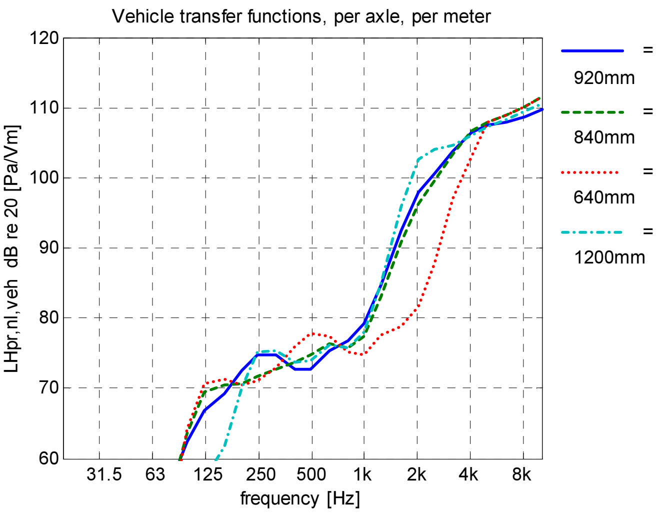


***Figure 6**: Vehicle transfer functions ($L_{Hpr,nl}$), calculated with TWINS for different wheel diameters.*

***Table** 7: Tabulated track transfer functions*

Freq. [Hz]	mono/soft	mono/med	mono/stiff	bibl/soft	bibl/med	bibl/stiff	Wood
20	20	17	16	17	16	16	11
25	26	23	22	23	22	22	17
32	32	29	28	29	28	28	23
40	38	35	34	35	34	34	29
50	43,9	41,5	40,7	41,5	40,6	40,4	34,6
63	49,0	47,5	46,9	46,3	45,8	45,6	40,7
80	54,1	53,4	53,2	51,2	51,0	50,9	46,8
100	60,8	61,7	62,1	57,2	57,4	57,4	55,7
125	65,9	67,6	68,3	62,1	62,5	62,6	61,8
160	68,5	70,0	70,7	65,2	65,8	66,1	63,8
200	70,7	72,3	73,0	68,3	70,1	70,9	63,7
250	73,3	74,7	75,4	71,3	73,4	74,4	65,6
316	75,9	76,5	77,0	74,0	74,5	75,1	70,2
400	78,3	77,7	78,1	75,7	73,5	74,0	76,3
500	80,9	79,5	79,7	78,4	74,5	74,7	80,9
630	84,1	82,3	81,9	82,4	78,7	78,0	83,6
800	88,3	86,0	84,6	88,3	84,9	82,2	87,1
1000	91,5	88,8	86,9	92,3	89,1	85,5	89,8
1250	92,7	90,4	88,6	93,3	90,7	87,8	90,9
1600	93,9	92,2	90,8	94,2	92,5	90,8	91,8
2000	95,1	93,7	92,5	95,2	94,2	93,1	92,9
2500	95,1	94,0	93,0	95,3	94,4	93,6	93,2
3160	95,0	94,1	93,2	95,1	94,4	93,7	93,4
4000	95,0	94,4	93,7	95,1	94,7	94,1	93,7
5000	94,8	94,4	93,9	94,8	94,5	94,1	93,6
6350	94,4	94,3	94,1	94,3	94,2	94,0	93,5
8000	94,1	94,3	94,4	94,0	94,0	93,9	93,5
10000	93,9	94,3	94,7	93,7	93,8	93,9	93,5

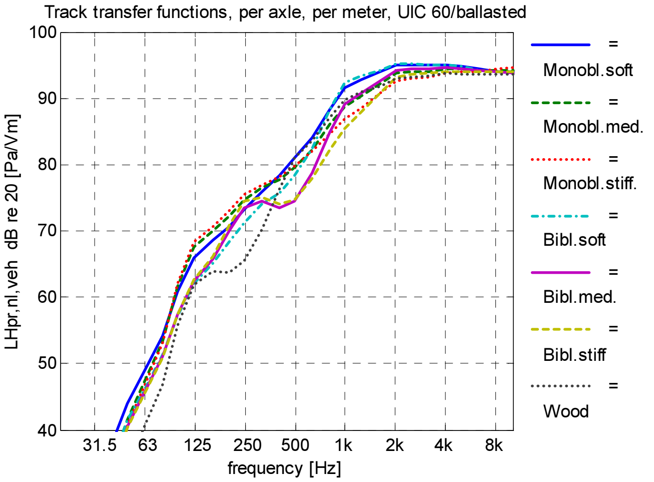
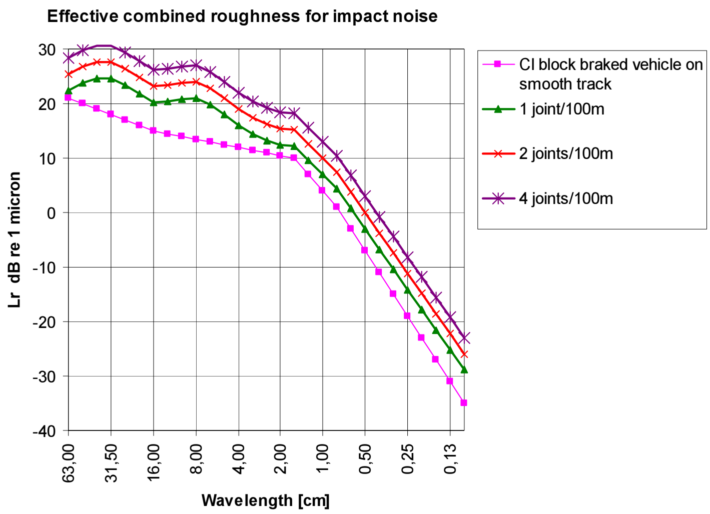


***Figure** 7: Track transfer functions ($L_{Hpr,nl}$), calculated with TWINS for different track types, all ballasted with UIC60 rail: Monoblock, biblock or wooden sleepers, soft medium or stiff railpads.*

3.3 Defaults for impact noise

Default normalised impact roughness $L_{r,impact,nl}(\lambda)$ is given for a single average joint impact level, for an impact density $n_l=0.01$ (1 impact per 100 meters track). Other values for the impact roughness may be obtained by measurement. The factor of joint density is used to take the number of impacts per unit length of track into account. In the graph below, the impact roughness is given for $n_l=0.01$, 0.02, and 0.04.



Wavelength [cm]	63,0	50,0	40,0	31,5	25,0	20,0	16,0	12,0	10,0	8,0	6,3	5,0	4,0	3,20	2,50	2,00	1,60	1,20	1,00	0,80	0,63	0,50	0,40	0,32	0,25	0,20	0,16	0,13	0,10
Lrimpact,nl	22,4	23,8	24,7	24,7	23,4	21,7	20,2	20,4	20,8	20,9	19,8	18,0	16,0	14,4	13,2	12,5	12,1	9,5	7,0	4,4	0,7	-3,0	-6,7	-10,4	-14,1	-17,8	-21,5	-25,2	-28,9

***Figure 8**: Impact roughness curves for different rail joint densities*

It should be noted that points and multiple points should be modelled by taking an adequate joint density over a relevant length of track. The approximate joint density to be taken for different situations is given in table 8.

***Table 8**: Joint density defaults for different situations*

Joint situation	Joint density n_l
Single joint in normal track	0.01
Jointed track, joint density n_l	n_l
1 set of points	0.03
2 sets of points per 100m	0.06
Multiple sets of points, railway junction	0.08

The data used here is in part derived from the Dutch SRM II calculation method, although modified with the joint density and approach for impact roughness.

3.4 Defaults for traction noise

Some traction data source data are given here for relevant operating conditions for diesel locomotives, electric locomotives, DMUs and EMUs. The source data given does not include rolling noise, which can exceed the traction noise above certain speeds or roughness conditions. Care should be taken when using this data as a default for traction noise as it may differ significantly from type to type. For example, the traction noise from a disel locomotive with known mechanical power may differ significantly between different designs.

The data is derived from measured data, smoothed and transformed to different operating conditions where necessary. All traction noise data in the following sections is tabulated together in table 9.

3.4.1 Diesel locomotives

Several spectra are given for different diesel electric locomotives, with various mechanical power, number of axles, length and weight. The frequency peaks below 100 Hz are generally associated with the exhaust. The medium frequency range tends to be dominated by a combination of colling fan noise and radiated engine noise. Peaks above 1 kHz are often related to turbochargers, which set in during loaded conditions.

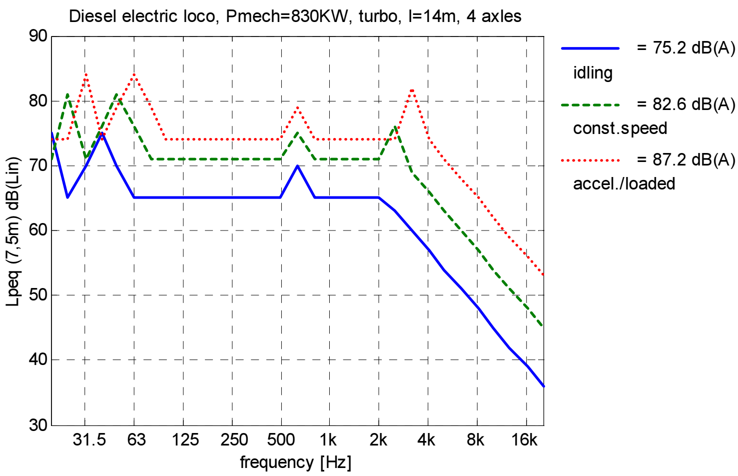


Figure 9: *Traction noise for a 830 KW, 4-axle diesel electric locomotive at idling, constant speed and acceleration conditions.*

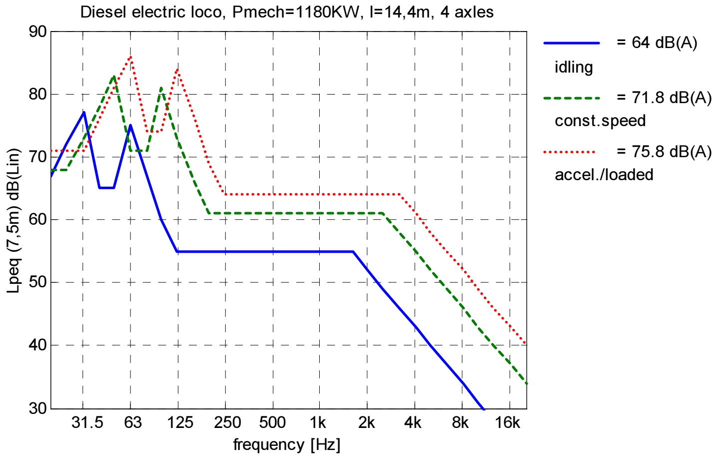


Figure 10: *Traction noise for a 1180 KW, 4-axle diesel electric locomotive at idling, constant speed and acceleration conditions.*

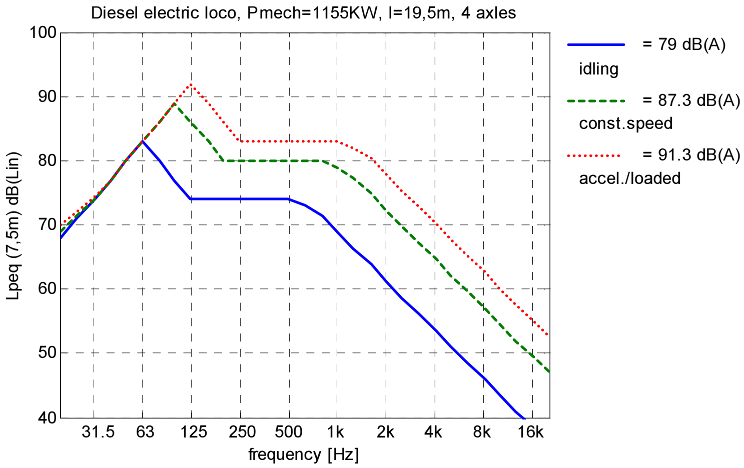


Figure 11: *Traction noise for a 1155 KW, 4-axle diesel electric locomotive at idling, constant speed and acceleration conditions.*

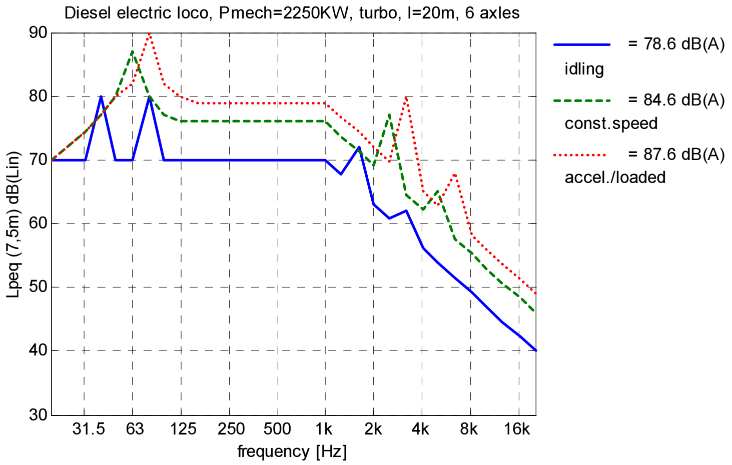


Figure 12: *Traction noise for a 2250 KW, 6-axle diesel electric locomotive at idling, constant speed and acceleration conditions.*

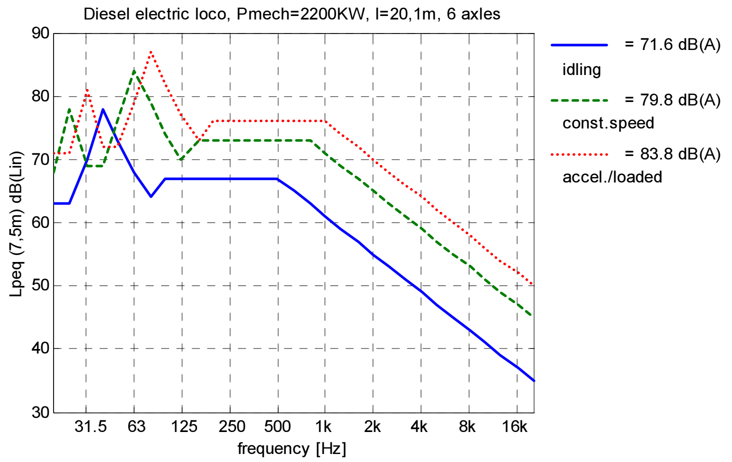


Figure 13: *Traction noise for a 2200 KW, 6-axle diesel electric locomotive at idling, constant speed and acceleration conditions.*

3.4.2 Electric locomotives

Electric locomotives can have strong fan noise, gear noise and electrical converter noise. An example is given here for a general purpose electric locomotive with high fan noise and converter noise. The locomotive has 4560 KW mechanical power, a length of 17,6m and has 4 axles and a total weight of 86 tons.

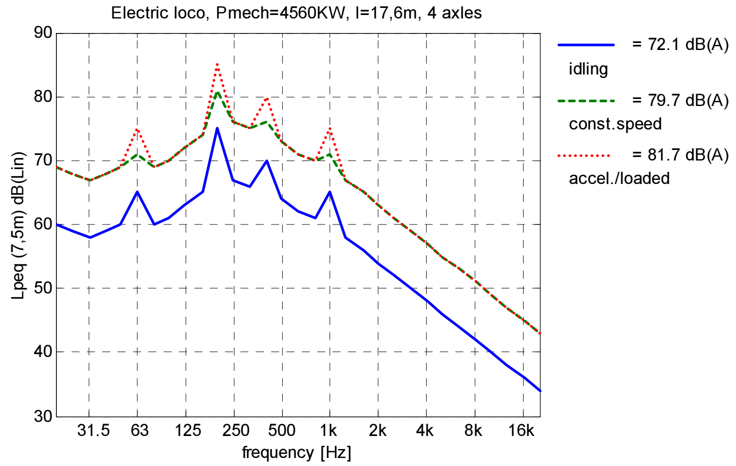


Figure 14: *Traction noise for a 4560 KW, 4-axle electric locomotive at idling, constant speed and acceleration conditions.*

3.4.3 Diesel Multiple Units (DMUs)

Source data is given for a diesel electric DMU with two coaches, each powered with a diesel engine mounted underneath the chassis (therefore not well shielded). The total mechanical power is 640 KW, total weight 94 tons, total length 52,3m. The diesel engine noise often dominates the overall noise.

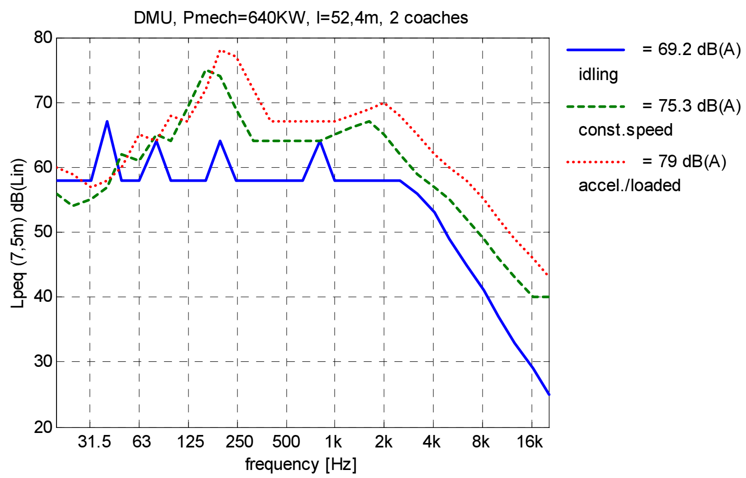


Figure 15: *Traction noise for a 640 KW, 2 coach diesel multiple unit at idling, constant speed and acceleration conditions.*

3.4.4 Electrical Multiple Units (EMUs)

Source data is given for an electrical multiple unit with two coaches, each powered with an electric motor and a gear transmission mounted on the axle. The total mechanical power is 508 KW, total weight 88 tons, total length 52,1m. Gear noise is predominant at speed, while generator fans dominate noise at standstill, with a small contribution from compressors.

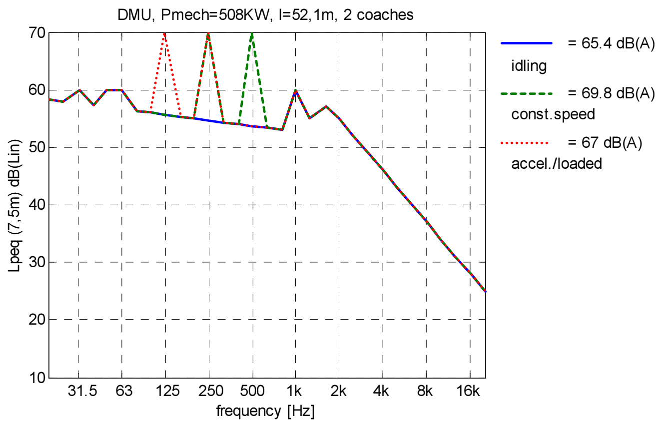


Figure 16: *Traction noise for a 508 KW, 2-coach electrical multiple unit at idling, constant speed and acceleration conditions.*

3.4.5 Tabulated traction noise data

The tabulated source data for the vehicles from the previous sections is given in table 9 below.

Table 9a: traction noise source data for selected powered vehicles

	Diesel loco SNCF BB66400 Pmech =830 KW vmax=120 km/h M =64 ton L=14 m			Diesel loco SNCF CC72000 Pmech 2250 KW vmax=160 km/h M=114 ton L=20m			Diesel loco RENFE Dloco Pmech=1155 KW vmax=125 km/h L=19,5m			Diesel loco NS6400 Dloco Pmech=1180 KW vmax=125 km/h W= 82 ton L=14,4m		
Frequency [Hz	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.
20	75,0	71,0	74,0	70,0	70,0	70,0	68,0	69,0	70,0	67,0	68,0	71,0
25	65,0	81,0	74,0	70,0	72,0	72,0	71,0	71,5	72,0	72,0	68,0	71,0
32	70,0	71,0	84,0	70,0	74,5	74,5	74,0	74,0	74,5	77,0	73,0	71,0
40	75,0	76,0	74,0	80,0	77,0	77,0	77,0	77,0	77,0	65,0	78,0	76,0
50	70,0	81,0	79,0	70,0	80,0	80,0	80,0	80,0	80,0	65,0	83,0	81,0
63	65,0	76,0	84,0	70,0	87,0	82,0	83,0	83,0	83,0	75,0	71,0	86,0
80	65,0	71,0	79,0	80,0	80,0	90,0	80,0	86,0	86,0	67,0	71,0	74,0
100	65,0	71,0	74,0	70,0	77,0	82,0	77,0	89,0	89,0	60,0	81,0	74,0
125	65,0	71,0	74,0	70,0	76,0	80,0	74,0	86,0	92,0	55,0	73,0	84,0
160	65,0	71,0	74,0	70,0	76,0	79,0	74,0	83,0	89,0	55,0	66,0	76,0
200	65,0	71,0	74,0	70,0	76,0	79,0	74,0	80,0	86,0	55,0	61,0	69,0
250	65,0	71,0	74,0	70,0	76,0	79,0	74,0	80,0	83,0	55,0	61,0	64,0
315	65,0	71,0	74,0	70,0	76,0	79,0	74,0	80,0	83,0	55,0	61,0	64,0
400	65,0	71,0	74,0	70,0	76,0	79,0	74,0	80,0	83,0	55,0	61,0	64,0
500	65,0	71,0	74,0	70,0	76,0	79,0	74,0	80,0	83,0	55,0	61,0	64,0
630	70,0	75,0	79,0	70,0	76,0	79,0	73,0	80,0	83,0	55,0	61,0	64,0
800	65,0	71,0	74,0	70,0	76,0	79,0	71,4	80,0	83,0	55,0	61,0	64,0
1000	65,0	71,0	74,0	70,0	76,0	79,0	68,9	79,0	83,0	55,0	61,0	64,0
1250	65,0	71,0	74,0	67,7	73,7	76,7	66,3	77,4	82,0	55,0	61,0	64,0
1600	65,0	71,0	74,0	72,0	71,4	74,4	63,8	74,9	80,4	55,0	61,0	64,0
2000	65,0	71,0	74,0	63,1	69,1	72,1	61,2	72,3	77,9	52,0	61,0	64,0
2500	63,0	76,0	74,0	60,8	77,0	69,8	58,7	69,8	75,3	49,0	61,0	64,0
3150	60,0	69,0	82,0	62,0	64,5	80,0	56,1	67,2	72,8	46,0	58,0	64,0
4000	57,0	66,0	74,0	56,1	62,1	65,1	53,6	64,7	70,2	43,0	55,0	61,0
5000	54,0	63,0	71,0	53,8	65,0	62,8	51,0	62,1	67,7	40,0	52,0	58,0
6300	51,0	60,0	68,0	51,5	5,8	68,0	48,5	59,6	65,1	37,0	49,0	55,0
8000	48,0	57,0	65,0	49,2	55,2	58,2	46,0	57,0	62,6	34,0	46,0	52,0
10000	45,0	54,0	62,0	46,9	52,9	55,9	43,5	54,5	60,0	31,0	43,0	49,0
12500	42,0	51,0	59,0	44,6	50,6	53,6	41,0	52,0	57,5	28,0	40,0	46,0
16000	39,0	48,0	56,0	42,3	48,3	51,3	38,5	49,5	55,0	25,0	37,0	43,0
20000	36,0	45,0	53,0	40,0	46,0	49,0	36,0	47,0	52,5	22,0	34,0	40,0

Table 9b: traction noise source data for selected powered vehicles

	Diesel loco TKOJ JT42CWR/Class66 Pmech=2200 KW vmax=121 km/h W= 126 ton L=20,1 m			DMU NS DM90 DMU Pmech=640 KW vmax=140 km/h W= 94 ton L=52,3 m			Eloco NS 1700 Eloco Pmech=4560 KW vmax=140 km/h W= 86 ton L=17,6 m			EMU NS Mat64 EMU Pmech=508 KW vmax=140 km/h W= 82 ton L=52,1 m		
Frequency [Hz	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.	Idling	Cst.Speed	Accel.
20	63,0	68,0	71,0	58,0	56,0	60,0	60,0	69,0	69,0	58,3	58,3	58,3
25	63,0	78,0	71,0	58,0	54,0	59,0	59,0	68,0	68,0	58,0	58,0	58,0
32	70,0	69,0	81,0	58,0	55,0	57,0	58,0	67,0	67,0	60,0	60,0	60,0
40	78,0	69,0	72,0	67,0	57,0	58,0	59,0	68,0	68,0	57,3	57,3	57,3
50	73,0	76,0	72,0	58,0	62,0	60,0	60,0	69,0	69,0	60,0	60,0	60,0
63	68,0	84,0	79,0	58,0	61,0	65,0	65,0	71,0	75,0	60,0	60,0	60,0
80	64,0	79,0	87,0	64,0	65,0	64,0	60,0	69,0	69,0	56,3	56,3	56,3
100	67,0	74,0	82,0	58,0	64,0	68,0	61,0	70,0	70,0	56,0	56,0	56,0
125	67,0	70,0	77,0	58,0	69,0	67,0	63,0	72,0	72,0	55,6	55,6	70,0
160	67,0	73,0	73,0	58,0	75,0	72,0	65,0	74,0	74,0	55,3	55,3	55,3
200	67,0	73,0	76,0	64,0	74,0	78,0	75,0	81,0	85,0	55,0	55,0	55,0
250	67,0	73,0	76,0	58,0	69,0	77,0	67,0	76,0	76,0	54,6	70,0	70,0
315	67,0	73,0	76,0	58,0	64,0	72,0	66,0	75,0	75,0	54,3	54,3	54,3
400	67,0	73,0	76,0	58,0	64,0	67,0	70,0	76,0	80,0	54,0	54,0	54,0
500	67,0	73,0	76,0	58,0	64,0	67,0	64,0	73,0	73,0	53,6	70,0	53,6
630	65,0	73,0	76,0	58,0	64,0	67,0	62,0	71,0	71,0	53,3	53,3	53,3
800	63,0	73,0	76,0	64,0	64,0	67,0	61,0	70,0	70,0	53,0	53,0	53,0
1000	61,0	71,0	76,0	58,0	65,0	67,0	65,0	71,0	75,0	60,0	60,0	60,0
1250	59,0	69,0	74,0	58,0	66,0	68,0	58,0	67,0	67,0	55,0	55,0	55,0
1600	57,0	67,0	72,0	58,0	67,0	69,0	56,0	65,0	65,0	57,0	57,0	57,0
2000	55,0	65,0	70,0	58,0	65,0	70,0	54,0	63,0	63,0	55,0	55,0	55,0
2500	53,0	63,0	68,0	58,0	62,0	68,0	52,0	61,0	61,0	52,0	52,0	52,0
3150	51,0	61,0	66,0	56,0	59,0	65,0	50,0	59,0	59,0	49,0	49,0	49,0
4000	49,0	59,0	64,0	53,0	57,0	62,0	48,0	57,0	57,0	46,0	46,0	46,0
5000	47,0	57,0	62,0	49,0	55,0	60,0	46,0	55,0	55,0	43,0	43,0	43,0
6300	45,0	55,0	60,0	45,0	52,0	58,0	44,0	53,0	53,0	40,0	40,0	40,0
8000	43,0	53,0	58,0	41,0	49,0	55,0	42,0	51,0	51,0	37,0	37,0	37,0
10000	41,0	51,0	56,0	37,0	46,0	52,0	40,0	49,0	49,0	34,0	34,0	34,0
12500	39,0	49,0	54,0	33,0	43,0	49,0	38,0	47,0	47,0	31,0	31,0	31,0
16000	37,0	47,0	52,0	29,0	40,0	46,0	36,0	45,0	45,0	28,0	28,0	28,0
20000	35,0	45,0	50,0	25,0	40,0	43,0	34,0	43,0	43,0	25,0	25,0	25,0

3.5 Default for broadband braking noise

A default for broadband braking noise is given at 80 km/h, which is only relevant for cast-iron block-braked vehicles:

$$L_{p,brake,i}(v) = 88 + 30\ lg\ (v/80) \quad @800\text{-}8000\ Hz \tag{22}$$

3.6 Default for brake squeal

A default for brake squeal is given for any vehicles known to have brake squeal below speeds where mechanical braking sets in. This value is a constant spectrum:

$$L_{pbrakesqueal,i} = 100\ dB\ @\ 1kHz \tag{23}$$

3.7 Defaults for curve squeal

Two defaults are given for curve squeal, one for large radius curves and one for sharp curves such as in points. These defaults include an assumed statistical occurrence and average number of wheels squealing.

Currently proposed defaults for curve squeal are:

$$L_{peq,curve\ squeal,\ points,i} = 100\ dB\ @\ 1kHz,\ 2kHz\ ,\ for\ v=40km/h\ and\ R=40m \tag{24}$$

$$L_{peq,curve\ squeal,curve,i} = 95\ dB\ @\ 2kHz\ ,\ 4kHz,\ for\ v=80km/h\ and\ R=250m \tag{25}$$

3.8 Defaults for aerodynamic noise

Defaults for aerodynamic noise are give at two source heights, 0,5m and 4m. The sources at both heights are broadband but the source at bogie level 0,5m has more low frequency content.

$$L_{peq,aero,i}(v,h=0,5m)=63+\ 60\ lg(v/80)\ @20\text{-}8000Hz \tag{26}$$

$$L_{peq,aero,i}(v,h=4m)=65+60\ lg(v/80)\ @4000\text{-}5000Hz \tag{27}$$

4 Measurement protocol

4.1 Introduction

As the measurement effort for source strength can easily become too large, it is important to allow elimination of sources if it can be shown that they are generally not relevant, or if no measurement is done, default values (see chapter 3) should be assumed.

The procedure consists of the following steps:

a) Determine which noise sources are relevant for the vehicle in question and which operating conditions are required.
b) Determine the partial source contributions either by measurement or by default values. Measurements are performed in accordance to prEN ISO 3095:2001 with exceptions and additions as described below.
c) Determine total emission source strength for partial contributions and in terms of sound power per meter (see chapter 2).

Some sources that cannot be measured easily or are difficult to control may need to be measured during standstill, especially intermittent sources such as compressors and valves. This is described further in [3].

Additional information on the available tools and measurement techniques can be found in IMAGINE report IMA6TR-041114-AEATNL01 / Imagine - practical measurement guidelines & analysis [4].

Source contributions are each allocated to one or more characteristic source heights.
The source height is determined either by physical position or by means of special measurements such as microphone arrays or others.

Each source type requires a specific measurement as indicated in the table below and in the following sections. This table can also be used to check which source types are relevant for a particular vehicle.

***Table 10**: Overview of measured quantities and conditions.*
prEN ISO3095:2001 is applicable unless otherwise stated.

Source type	**Measured quantities**	**Operating condition**	**Microphone position**	**Accelerometer position**	**Track requirement**
Rolling noise	v, L_{peqTp}, L_{veqTp}, D_s, N_{ax}/l_{veh} $L_{r,rail}$ $L_{Hpr\ nl}$ *for track* (with reference vehicle or other method)	Pass-by at several speeds One or more speeds between 50<v<250kmh Minimum of 3 recommended	D=7.5m, H=1.2m [D=1.75, H=0m]	L1,[L2], V1,[V2],[S1] dependent on method	ISO3095 or TSI compliant
Impact noise	v, N_{ax}/l_{veh} ΔL_{peqTp}, ΔL_r (impact/rolling)	Pass-by(s) with and without rail joint	D=7.5m, H=1.2m At joint	N/A	Joint, crossing or points
Traction noise total	$L_{peqTp,traction,idling}$ $L_{peqTp,traction,acceleration}$ $L_{peqTp,traction,const.\ speed}$ $L_{peqTp,traction,deceleration}$	Stationary Acceleration Constant speed Deceleration	D=7.5m, H=1.2m L=0m, 20 m (20m for acc./dec.)	N/A	ISO3095 compliant
Traction noise, drive (optional)	L_{peqTp}, n_{drive} , v	Pass-by, acceleration or stationary	D=7.5m, H=1.2m L=0+20 m	N/A	ISO3095 compliant
Traction noise, fan (optional)	L_{peqTp}, n_{fan}, d_{fan}	Stationary	D=7.5m, H=1.2m L=Box or L=0m	N/A	ISO3095 compliant
Traction noise, other (optional)	L_{peqTp}, d_i	Stationary	D=7.5m, H=1.2m L=Box or L=0m	N/A	ISO3095 compliant
Deceleration noise, braking	L_{peqTp}, v	Deceleration from maximum and service speeds	D=7.5m, H=1.2m L=0m	N/A	ISO3095 compliant
Deceleration noise, squeal	L_{peqTp}, v	Deceleration from 50 km/h 25 km/h	D=7.5m, H=1.2m L=0m	N/A	[ISO3095 compliant]
Curve squeal	L_{peqTp}, v	Curve pass-bys in points (10,20,40km/h) curve (80,120 km/h)	D=7.5m, H=1.2m L=0m	N/A	In points and/or curve R<1000m
Aerodynamic noise	L_{peqTp}, v	Pass-by at high speeds	D=25m, H=3.5m Convert to 7,5m	N/A	ISO3095 or TSI compliant

4.2 Rolling noise

4.2.1 Transfer functions

The **track transfer function** $L_{Hpr,nl,tr,i}$ and the **vehicle transfer function** $L_{Hpr,nl,veh,i}$ are determined from pass-by measurements containing only rolling noise. Other sources must not be present, must be switched off or minimised during the measurement.

Note that in the following all roughness L_r refers to effective (filtered) roughness unless otherwise indicated by index *dir* for direct roughness.

The **total** transfer function $L_{Hpr,nl,i}$ can be determined from the ratio between the pass-by sound pressure level $L_{peq,i}(v)$ at 7.5m distance from the track centreline, 1.2m above the rail surface, and the **total effective roughness** $L_{rtot}(f_i,v)$:

$$L_{Hpr,nl,i} = L_{peq,i}(v) - L_{rtot,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \tag{28}$$

This can be measured from a single pass-by or averaged over a number of pass-bys, and will contain a contribution from the track and from the vehicle.

Sound pressure measurement is straightforward, total effective roughness is obtained from the equivalent vertical railhead vibration level (see 2.4 for key to symbols).

$$L_{rtot,i}(v) = L_{veq,i}(v) + 10\lg\left(\frac{D_{si}}{8.68N_{ax}/l_{veh}}\right) - A_{2,i} - 20\lg(2\pi f_i) \tag{29}$$

The **track** transfer function must be obtained by using the track contribution $L_{peq,tr}$ in formula (6). This can be done in different ways:

- by using a reference vehicle (see [2] and Appendix 1)
- by other separation techniques
- or by using a distribution function calculated for example with TWINS.

This will then result in:

$$L_{Hpr,nl,tr,i} = L_{peq,tr,i}(v) - L_{rtot,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \tag{30}$$

$$L_{Hpr,nl,veh,i} = L_{peq,veh,i}(v) - L_{rtot,i}(v) - 10\lg\frac{N_{ax}}{l_{veh}} \tag{31}$$

For a given network or known test site, the track transfer function might only have to be measured once or occasionally, after which it is well known or even tabulated. It should be independent from the train speed.

If only the total transfer function and the track transfer function are known, the vehicle transfer function may be estimated by using an estimated vehicle contribition $L_{pveh}(f)$ (omitting subscript *eq)*:

$$L_{pveh,i} = 10\lg(10^{Lptoti/10} - 10^{Lptri/10})$$
$$\text{and if } L_{ptot,i} - L_{ptr,i} < 1: \quad L_{pveh,i} = L_{ptot,i} - 7 \text{ and } L_{ptr,i} = L_{ptot,i} - 1 \qquad (32)$$

Now the vehicle and track contributions $L_{peq,veh,i}(v)$ and $L_{peq,tr,i}(v)$ can be calculated for any roughness condition, speed, and axle density (N_{ax}/l_{veh} = axles/unit length):

$$\begin{aligned} L_{peq,tr,i}(v) &= L_{rtot,i}(v) + L_{Hpr,nl,tr,i} + 10\lg\frac{N_{ax}}{l_{veh}} \\ L_{peq,veh,i}(v) &= L_{rtot,i}(v) + L_{Hpr,nl,veh,i} + 10\lg\frac{N_{ax}}{l_{veh}} \end{aligned} \qquad (33)$$

If the total effective roughness includes the average network effective rail roughness $L_{rtr,net}$,
then a prediction for the noise level under average network conditions is obtained (see also *(4)* in 2.4)

4.2.2 Roughness

The total effective roughness for the average network situation $L_{rtot,net}(\lambda)$ is determined as follows:

$$L_{rtot,net}(\lambda) = L_{rveh}(\lambda) \oplus L_{rtr,net}(\lambda) \qquad (34)$$

where $\oplus$ indicates energy summation and $L_{rtr,net}(\lambda)$ is the effective rail roughness for the network. The effective wheel roughness $L_{rveh}(\lambda)$ is estimated from

$$L_{rveh}(\lambda) = 10\lg(10^{Lrtot(\lambda)/10} - 10^{Lrtr(\lambda)/10})$$
$$\text{and if } L_{rtot}(\lambda) - L_{rtr}(\lambda) < 1: \quad L_{rveh} = L_{rtot}(\lambda) - 7 \text{ and } L_{rtr}(\lambda) = L_{rtot}(\lambda) - 1 \qquad (35)$$

where $L_{rtr}(\lambda)$ is the rail roughness at the (smooth) measurement site. The effective wheel roughness can also be measured from a pass-by on a smooth track, where it can be demonstrated that the total roughness of the vehicle in question is above the lowest found total roughness from multiple pass-bys of various other vehicles.

The effective rail roughness for the network is chosen as a default spectrum, typical for the country in question (see appendix for example of the Netherlands).

4.3 Impact noise

The impact roughness $L_{rimpact}(\lambda)$ can be be determined by measuring the pass-by noise from a vehicle with ($L_{peq,Tp,impact}$) and without ($L_{peq,Tp,roll}$) a rail joint. Also the total effective roughness for the pass-by without joint $L_{r,roll}$ must be determined. The normalised impact roughness level $L_{rimpact,nl}$ for 1 joint per 100m can be then obtained from:

$$L_{rimpact,nl} = L_{r,roll} + L_{peq,Tp,impact} - L_{peq,Tp,roll} - 10 \lg (N_{ax}/l) - 20 \qquad (36)$$

where N_{ax} is the total number of axles measured in the pass-by and l is the total length of the train.

Different characteristic impact roughness may be found for track joints, points and crossings, as the geometry and impact amplitude may differ.

The track noise L_{ptr} is allocated to h=0m, the vehicle rolling L_{pveh} noise to h=0,5m.

4.4 Bridge noise

For bridges, the track transfer function must be determined by measurement in the same way as is done for a track.

4.5 Traction noise

Traction noise can be measured for each operating condition including idling, acceleration from standstill, constant speed and if relevant, deceleration. This will result in the spectral quantities

$L_{peqTp,traction,idling}$
$L_{peqTp,traction,acceleration}$
$L_{peqTp,traction,const.\ speed}$
$L_{peqTp,traction,deceleration.}$

The tests for all these conditions are performed according to prEN ISO 3095, with the following exceptions:

- for the acceleration test, $L_{peq,Tp}$ is determined for both microphones at 0m and 20m, and the energy average of both is taken as the result.
- The same is done for the deceleration test, which is only relevant for traction noise if the traction noise is significant (e.g. regenerative braking, diesel at lower rpm).
- for both acceleration and deceleration tests, locomotives are loaded with a load at least 5 times their own weight.
- For the standstill test, for vehicles with multiple microphones positions, those positions with low noise levels can be left out, for example for fixed trainsets. This can be compensated in the calculated measurement results as follows:

$$L_{pAeq} = 10\,lg\,(\sum_i 10^{L_{pi}/10} . \ell_i / \ell_{total}) \tag{37}$$

where L_{pi} is the measured sound pressure level for each measurement surface around the vehicle, l_i is the length of the *i-th* measurement surface along the train and l_{total} is the total length of the measurement surface around the train at 7,5m distance.

- As an alternative to the standstill test it is also possible to perform a dead-slow measurement at 2-6 km/h with two microphones either side of the vehicle, with all equipment in normal operation. The energy average of the two positions is taken.

If it is difficult to perform running measurements or to derive or separate out the traction noise, it may be simpler to take only stationary measurements, for which the traction noise is dominant. However, in that case, the equipment operating conditions have to be simulated, for example by running a diesel engine or a fan at higher speeds during standstill. Procedures to do this are given in the following.

For noise from the powertrain, $L_{pdrive,nmax,i}$ has to be determined for a maximum drive rpm $n_{drive,max}$ (or the nearest feasible rpm) and the factor C_{drive} has to be determined from 2 or more operating points.

For fan noise $L_{pfan,nmax}$ has to be determined for a maximum drive rpm $n_{fan,max}$ (or the nearest feasible rpm) and the factor C_{fan} has to be determined from 2 or more operating points (similar to traction noise).

This data can be determined either from standstill, acceleration or pass-by tests.

- For standstill testing, for example on diesel-powered vehicles, measurements are performed for drive rpms at idling, 25%, 50%, 75% and 100% of the rpm range, or as far as practicably allowable.
- For acceleration tests, measurements are collected at several microphone positions along the track, at 0 and 20m from the front of the train. Optionally, 10m and 30m can be added if signficant differences are expected. Fan and drive speeds are determined together with corresponding sound powers, if possible also at maximum driveshaft speed for diesels or maximum fan speed for electrically powered vehicles.
- If a constant speed test is used, the driveshaft speed or fan speed needs to be determined, as appropriate. The vehicle should be operated with a characteristic load and for several speeds up to the speed range where traction noise no longer dominates.

For any other traction or auxiliary sources j with non-continuous or intermittent operation the characteristic duration d_j and fixed level $L_{pj,i}$ need to be measured. This will often be possible with a stationary test during which such sources are active.

If specific characteristic operating points of the relevant sources are known, these may be used.

4.6 Deceleration noise

For braking noise with speed dependency, at least two measurements at different speed are required whilst braking; one at reference speed v_0 to determine $L_{pbrake,i}(v_0)$ and another to determine the speed dependency factor C_{brake}.

For brake squeal the squeal noise level $L_{psqueal,i}$ and its duration correction d_{squeal} for the relevant period need to be measured, and the speeds at which brake squeal occurs.

4.7 Curve squeal

As with aerodynamic noise, curve squeal only needs to be characterised if it actually occurs at all and is required for certain situations.

Curve squeal noise is measured in a) a set of points and b) in a curve with a radius of betwen 500-1000m. A microphone is placed at 7,5m either side of the curve, at its sharpest point. The rail surface must be dry. There are no requirements for the rail roughness, although there should be no severe wear or rail corrugation.

The pass-by level $L_{peq,Tp,i}$ is measured. 5 pass-bys are taken for each speed. 2-3 characteristic speeds are taken: 10, 20 ,40 km/h for points, 80, 120 km/h for a curve. Only pass-bys with audible squeal are included. If possible, the 5 pass-bys can be made going back and forth (3 in one direction, 2 in the other). The results for each speed are arithmetically averaged. The results from each microphone are energy averaged. As curve squeal will not occur all of the time, 50% probability is assumed, so the measured average value is reduced by 3 dB.

Measurements taken in points may contain a significant contribution of impact noise. The squeal noise should be separated out by taking the tonal components in the spectrum.

The measurements result in $L_{psqueal,i}$ for points and for a curve of given radius. The levels can be converted approximately for speed and curve radius using the formula given in (20).

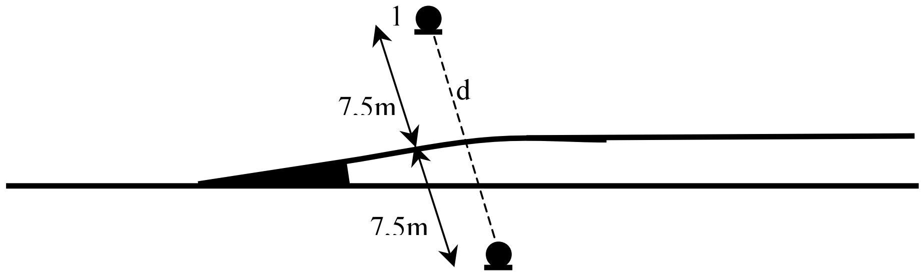


***Figure 17**: Microphone positions for measurement of curve squeal in points*

4.8 Aerodynamic noise

Aerodynamic noise can only be measured at high speeds and therefore it should first be verified whether it is actually relevant for prediction purposes. Once the rolling noise is properly characterised, it can be extrapolated to higher speeds and a comparison can be made with existing high speed data to check whether higher levels are produced by aerodynamic noise.

It is measured from 250 km/h in steps of 50km/h upwards. For practical reasons the measurement position often has to be 25m, so the sound pressure is converted back to 7,5m.
Special measurements are required to determine source height.

$L_{paero,i}(h)$ is determined from a curve fit in each third octave band for all measured speeds, resulting in

$$L_{paero,i}(h,v) = L_{paero,i}(h,v_0) + \alpha_i(h) lg\ (v/v_0) \tag{38}$$

where v_0 is a speed at which aerodynamic noise is dominant and $\alpha_i(h)$ is a coefficient determined from 2 or more measurement points.

5 Examples

In the following sections some examples are given of the source types and distribution which may typically be found on different types of rolling stock. If no measurement data is available, the default source data can be used. The sound power per unit length for each source height is determined by energy summation of each source type as in formula (2), at the relevant conditions.

At 0m there is always only the rolling noise contribution from the track. At 0,5m nearly all sources may occur. The source heights 2,3,4m are mainly relevant for traction and aerodynamic noise sources.

5.1 Unpowered passenger coaches

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		(x)	(x)	(x)	(x)	If auxiliary equipment relevant
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise		(x)				At speeds above 250 km/h

5.2 Freight wagons

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		(x)	(x)	(x)	(x)	If auxiliary equipment relevant
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise						N/a for frieght wagons

5.3 High speed train

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		x	x	x		
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise		x	x	x	x	At speeds above 250 km/h

5.4 Electric locomotive

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		x	x	x	x	
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise						

5.5 Diesel locomotive

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		x	x	x	x	
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise						

5.6 Electric passenger unit (EMU)

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		x			x	
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise						

5.7 Diesel passenger unit (DMU)

	0m	0,5m	2m	3m	4m	Remarks
Rolling/Joint noise	x	x				
Traction noise		x			x	
Curve squeal		x				Only in curves or points
Brake squeal		x				Only for deceleration
Braking noise		x				Only for deceleration
Aerodynamic noise						

6 Application notes

6.1 Linking up to existing national calculation schemes

The calculation model should allow the setting up of source models for national rolling stock by setting the various model parameters in such a way so as to obtain the same emission levels.

This requires a matching of available information on national rolling stock to physical parameters in the IMAGINE model, for example by setting the wheel roughness, average network roughness or transfer functions to a level that produces the corresponding noise level. The same can be done for the other sources.

In some cases it may be required to construct a source model of an equivalent vehicle, which represents a train type consisting of a locomotive and passenger coaches together. A similar exercise could be done for mixed freight trains.

6.2 National average rail roughness of the network

One of the quantities required for calculating noise levels on an 'average track', is the national average rail roughness level for the network. This is applied in the Dutch prediction method and is required in any method that takes rail roughness into account. In the Dutch case, average rail roughness was determined by taking a series of rail roughness measurements at about 30 different sites, and simply averaging these. This method could still be applicable if a rail roughness measurement device is available. An alternative method is to use a monitoring vehicle with smooth wheels (disc braked, no flats), measuring sound pressure due to rolling noise in the vehicle and calibrating the on-board sound pressure level at a site with the known total effective roughnes level at the same site. Then the network can be monitored over a number of representative routes at constant speed. The differences found in the sound pressure levels are directly related to the differences in total roughness. Once the ratio between total effective roughness and interior sound pressure level is established, an average total effective roughness can be determined from an averaged sound pressure level. This estimate is less accurate than direct measurements of rail roughness, but a much better average is obtained over the network. The estimate becomes better, the smoother the wheels are.

6.3 Characteristic or average operating conditions

When determining the source spectra for the various noise sources, especially traction noise requires special attention, as it needs to represent the average operating conditions. For example, the typical diesel rpm of a locomotive under acceleration conditions may be rather specific.

6.4 Intermittent sources

Intermittent or non-continuous sources need to be assessed in terms of duty cycle factor. Typically this requires information on the average operation time during acceleration, braking and constant speed.
It should be noted that over a long enough period, intermittent sources may reduce in significance compared to other continous sources.

6.5 Lack of measurement data

Sometimes rolling stock may not be available for source measurements as described previously. It may be possible to estimate source emission data with reduced effort. This does however require careful assessment of the individual physical sources, for example by checking whether they are masked out by certain other sources or not.

6.6 Availablity of a reference vehicle

A reference vehicle to determine the track transfer function may not always be available. There are other options to deal with this such as the use of calculations (e.g. TWINS) or special measurement tools (e.g. VTN). On the other hand such a measurement is not often required, certainly not each time a measurement is performed on the same track.

6.7 Availability of rail roughness measurement

Another issue of availability may be rail roughness measurement. This may be impossible due to lack of equipment, site access or simply cost. An alternative way of dealing with this is to measure the sound pressure level at 7,5m distance from the track centreline during a pass-by of unpowered passenger coaches at 80 km/h. If the level is below 77 dB(A) then the track may be assumed smooth enough. This will probably only be possible to achieve with disc-braked coaches. Powered trainsets with low traction noise may also possibly achieve such low levels.

6.8 Special track-vehicle combinations

Uncommon track designs and vehicles with bogie or wheel shrouds require special attention.
If a track-vehicle combination is unique, it is advisable to measure a total transfer function to characterise the rolling noise. The combination of track and vehicle noise shielding may complicate the separation of vehicle and track noise contributions.

On normal tracks, vehicles with bogie or wheel shrouds may also reduce the radiation from the track.
This should be taken into account by comparing the total transfer function for unshrouded and for shrouded vehicles and using the difference as a correction in the emission calculation.

6.9 Use of 'microphone only' data

In some cases measured railway noise data may only be available in the form of sound pressure level spectra, without information on roughness or rail vibration. Although less accurate, it may sometimes be possible to derive the source data from such measurements

The IMAGINE source model in its current state requires source information for operating conditions, physical sources, vehicle types and speeds, source heights and frequencies (spectrum).

The measured quantity is the $L_{peq,Tp}$. Each of the mentioned aspects can be dealt with as follows.
- Source height: This has to be estimated based on knowledge of the sources present and their physical location, i.e. rolling noise has sources at the wheels and the track, traction noise at axle height and fan height etc. If a source is in betweem the fixed heights, the sound power can be distributed between them.
- Vehicle type: source levels will be most accurate if noise sources are attributed to one vehicle type per measurement. If the sound pressure is measured for a whole train with different wagons or wagons/locomotive, it will be difficult to separate out physical sources afterwards.
- Operating conditions: This should generally be clear for vehicles and whole trains.
- Physical sources: For rolling noise, an estimate is needed for the roughness and the transfer functions. This is discussed under section 2. For other sources such as traction noise, aerodynamic noise, curve squeal and braking noise, these must be measured under conditions in which they are dominant.

If a whole train consisting of different vehicle types is characterised within one measurement, then it may contain different sources on different vehicles, e.g. locomotive (traction and rolling noise) versus coaches(rolling noise). This may be acceptable if a train configuration is fixed, however such configurations can be variable.

6.10 Estimating roughness and transfer functions from 'microphone only' data

In order to estimate roughness and transfer functions it is important to have a track or vehicle for which the data is known. It is also easier to deal with total roughness and transfer functions than the partial ones of vehicle and track.

Firstly, rolling noise must be dominant, which for unpowered coaches and wagons on a straight unjointed track will often be the case. Any given vehicle-track combination has a constant total transfer function $L_{Hpr,nl,i}$, so differences in noise level at different locations at the same speed and on the same track type can only be due to a change in total effective wheel-rail roughness $L_{r,tot,i}(v)$:

$$L_{p,i} = L_{r,tot,i}(v) + L_{Hpr,nl,i} + 10\ lg\ (N_{ax}/l_{veh}) \tag{39}$$

The total transfer function can be measured at a single location using a microphone and an accelerometer under the rail (see section 2.3.1, formula (10)). Alternatively it can be calculated using programs such as TWINS or approximated from a set of default data.

Once the transfer function of a given track-vehicle combination is known, it can be used to determine total effective roughness from any other pass-by measurement at another location on the same track type.

$$L_{rtot,i}(v) = L_p - L_{Hpr,nl,i} - 10\ lg\ (N_{ax}/l_{veh}) \quad (40)$$

With this approach it is now possible to compare total effective roughness levels from pass-bys at different locations. If significant differences are found, then an estimate of the effective wheel roughness $L_{r,wheel}$ can be made, as it will be no higher than the lowest found total roughness at several locations k:

$$L_{r,wheel} <= min\ (L_{r,tot,k}) \quad (41)$$

Once a total transfer function is known, it needs to be split into a track and vehicle transfer function. There are various ways of doing this. One is by using a default distribution function. This can be derived from calculation and given as a default in tabulated form (see below).

***Table 11**: Distribution functions to estimate track and vehicle transfer functions from total transfer function. For all frequencies below 63 Hz or above 2000 Hz the values at 63 Hz are valid (Dax = -1, Dtrack =-6,9).*

f_{centre} [Hz]	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000
D_{ax} [dB]	-1,0	-1,5	-2,0	-3,5	-5,0	-6,5	-7,0	-7,0	-7,0	-7,0	-6,5	-5,0	-3,5	-2,0	-1,5	-1,0
D_{track} [dB]	-6,9	-5,3	-4,3	-2,6	-1,7	-1,1	-1,0	-1,0	-1,0	-1,0	-1,1	-1,7	-2,6	-4,3	-5,3	-6,9

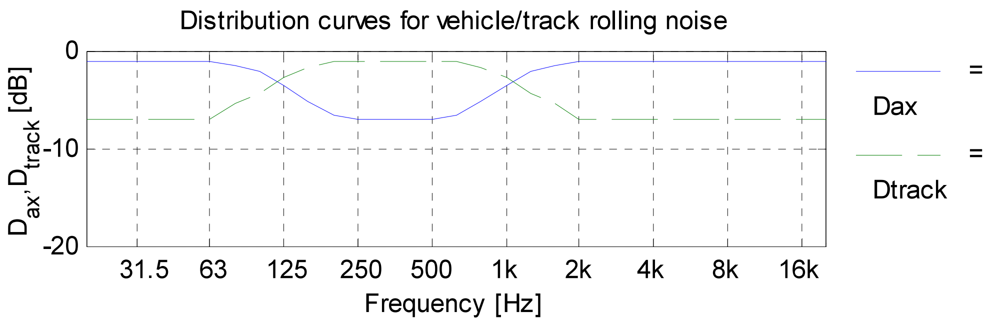


***Figure 18**: Distribution functions to estimate track and vehicle transfer functions from the total transfer function.*

With the above distribution functions, the track transfer function is

$$L_{Hpr,nl,\ tr} = L_{Hpr,nl,tot} + D_{track} \quad (42)$$

and the vehicle transfer function is

$$L_{Hpr,nl,\ veh} = L_{Hpr,nl,tot} + D_{ax} \qquad (43)$$

Another method is to measure the total transfer function at one location for vehicles with different wheels; the track contribution stays constant, but differences are seen in the vehicle contribution.

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Appendix A
Measurement of track transfer function, reference vehicle method and other separation techniques

Reference vehicle method to determine track transfer function

The reference vehicle method requires a separate pass-by with wagons with low sound radiation in comparison with the track. This can be achieved with massive wheels with diameters below 700mm and a vehicle with little or no superstructure, or well-isolated superstructure. Examples of such vehicles are given hereafter. A special transfer function $L_{Hpv,tr}(f)$ is measured during pass-by of the reference vehicles, between vertical railhead vibration and sound pressure. This function is not sensitive to the contact patch. It is used to derive the track contribution $L_{ptr}(f,v)$ of the normal test vehicle at speed v:

$$L_{ptr}(f,v) = L_{Hpv,tr}(f) + L_v(f) \tag{A1}$$

where $L_{Hpv,tr}(f)$ is the transfer function measured with the reference vehicle and $L_v(f)$ is the equivalent railhead vertical vibration level during pass-by. Now the track noise can be determined for any vehicle pass-by. The required track transfer function can now be obtained by dividing this track noise $L_{ptr}(f,v)$ of the test vehicle by its total effective roughness $L_{rtot}(f,v,)$, as determined in section 2.4 by formula (6).

Specification of the reference vehicle

A reference vehicle has the property that the vehicle transfer function or the sound contribution radiated by the vehicle is low in comparison to average vehicles, resulting in domination of the total noise level by the track. Consequently a track transfer function can be determined from a passby of such vehicles from the ratio between rail vibration and sound pressure.

Wagons with small diameter wheels will tend to radiate less sound than the track. In general, wagons with superstructure should be avoided or it should be checked that the superstructure is not contributing significantly to the noise radiation. Generally the superstructure tends not to contribute strongly.

Some examples of possible reference vehicles are given here which can be found on the European rail network:

-Nina: regional EMU which has 4 small-wheeled axles in the middle section with diameter smaller than 700 mm.
-Habbiks wagon: 4-axle closed freight wagon, wheel diameter 680 mm.
-Rola: 8 or 10-axle freight wagon truck transport (Rolling Highway), wheel diameter 380 mm.
-Megafret: 8- axle freight wagon, wheel diameter 780 mm.
-Novatrans: 8- axle freight wagon, wheel diameter 730 mm.
-Laekkqs547: 3- axle car transport wagon, wheel diameter 680 mm.

Other wagons can also be found. Wagons with small wheels often have a symbol of the wheel cross-section with the diameter marked on the outside of the framework.

Other methods to determine the track transfer function

It is also possible to derive the track transfer function by measuring the total transfer function, and then splitting it according to a distribution function. This can be done either by means of calculation or special measurement techniques for separation of track-vehicle noise radiation, for example VTN (developed in the STAIRRS project).

Appendix B Contact filter $A_2(\lambda)$, tabulated

Contact filter spectrum A_2 as a function of wavelength λ for several wheel diameters and wheel loads

Wavelength [cm]	360 mm / 50 kN	680 mm / 50 kN	920 mm / 50 kN	920 mm / 25 kN	920 mm / 100 kN
20	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0
12,5	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	-0.2	0.0	-0.2
6,3	0.0	-0.2	-0.5	-0.2	-0.6
5	-0.2	-0.4	-1.1	-0.5	-1.3
4	-0.5	-0.7	-1.9	-0.9	-2.2
3,15	-1.2	-1.5	-3.3	-1.6	-3.7
2,5	-2.0	-2.8	-5.0	-2.5	-5.8
2	-3.0	-4.5	-7.3	-3.8	-9.0
1,6	-4.3	-7.0	-9.8	-5.8	-12.5
1,25	-6.0	-10.3	-12.5	-8.5	-13.5
1	-8.4	-12.9	-13.8	-11.4	-13.5
0,8	-11.3	-13.6	-13.7	-12.6	-15.3
0,63	-11.9	-14.5	-15.1	-13.5	-16.4
0,5	-12.5	-15.5	-16.5	-14.5	-17.5
0,4	-13.9	-16.0	-16.4	-16.0	-18.4
0,315	-15.5	-16.5	-17.5	-16.5	-19.5
0,25	-17.0	-17.0	-17.8	-17.7	-20.5
0,2	-18.4	-17.5	-18.3	-18.6	-21.5
0,16	-19.9	-18.0	-18.8	-19.6	-22.4
0,125	-21.5	-18.5	-19.4	-20.6	-23.5
0,1	-22.9	-19.0	-19.8	-21.6	-24.5
0,08	-24.4	-19.5	-20.3	-22.6	-25.4
0,05	-27.4	-20.5	-21.4	-24.6	-27.5
0,04	-28.9	-21.0	-21.8	-25.6	-28.4

Appendix C
Relation between rail displacement and effective roughness $A_3(\lambda)$, tabulated

The level difference $A_3(f_{to})$ between the vibration displacement at the contact point $L_{x,contact}(f_{to})$ on the rail head and the combined effective roughness $L_r\ (V/f_{to})$, which describes to which extent roughness induces rail vibration, is the result of the wheel rail interaction.

$$A_3 = 20\log_{10}\left(\frac{|\alpha_R|}{|\alpha_R + \alpha_W + \alpha_C|}\right) \qquad \text{(C1)}$$

α_R : rail receptance, α_W : wheel receptance and α_C: receptance of the contact stiffness.
A_3 is tabulated below for typical pad stiffnesses.

Table C1: Spectra $A3_2(f_{to})$ for three categories of rail pad stiffness

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

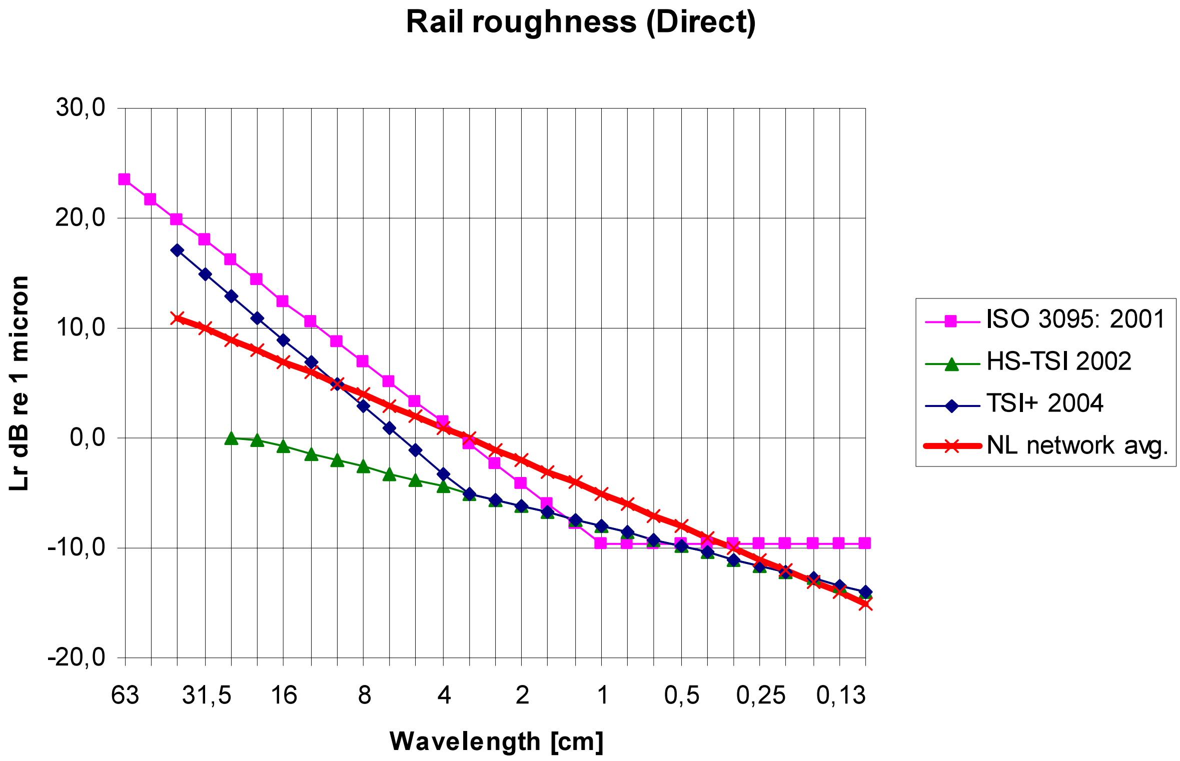
Table C2: Ranges of pad stiffness applying to different categories of pads used in defining standard spectra for A_3

	Soft pad	Medium pad	Stiff pad
bibloc sleeper	≤ 400 MN/m	400 - 800 MN/m	≥ 800 MN/m
monobloc sleepers	≤ 800 MN/m	≥ 800 MN/m	–
wooden sleepers	all	–	–

Frequencies where $|\alpha_R| » |\alpha_W+\alpha_C|$ give $A_3 \approx 0$ dB. This often occurs in practice between 100 and 1000 Hz. A study [3] using the TWINS model [4], shows that the spectrum A_3 in fact does depend slightly on the track properties. The pad stiffness is shown to be the most influential parameter. In the frequency range from 100 to 3150 Hz inclusive, the spectrum A_3 is listed in Table 2. Using these values A_3 is determined to an accuracy of ±3 dB for application to conventional wheels. This distribution is of course transferred to the result for the combined roughness. Since this does not lead to greater uncertainties than those found in conventional roughness measurements this is accepted. Averaging over more measurements with different train speeds further diminish this distribution since peaks and dips in frequency spectrum A_3 average out.

Appendix D Average rail roughness for the Netherlands

Average direct rail roughness for the Netherlands , as in SRM II 2004, is shown in the graph and table below, together with different rail roughness limits for test tracks.
Before using these spectra for the calculation model, the contact filter should be applied to obtain effective roughness.



Appendix E
Specification of the test track and implications for quality of measured data

For constant speed measurements the test track rail roughness should comply with pr EN ISO 3095:2001 or the TSI conventional rail (TSI+). The track type should be ballasted and have UIC60, UIC54 or similar rails. Sleepers should be concrete if possible. Railpads should be stiff if possible.

For all other measurements (i.e. stationary, acceleration, braking, curving, joints), a higher rail roughness is allowed, as long as the rolling noise does not dominate the source to be measured, such as traction, braking, or curve squeal noise. The rails should therefore not be corrugated.

The consequences of a rougher track will be higher measured noise levels and thereby partly too high noise emission data.

If a wooden sleeper track or concrete sleeper with soft railpads are used this may increase the measured noise levels by 2-3 dB(A). This is however not a problem if the derived noise emission data is only to be used for calculations on such tracks.