The IMAGINE Model for Railway Noise Prediction

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The EU project IMAGINE includes the further completion of the Harmonoise railway noise prediction model. In this paper the IMAGINE railway noise source model is described. Within the Harmonoise project, a model was proposed including most of the main railway noise sources. In IMAGINE, an improved formulation was put forward taking all physical sources but also operating conditions into account. At a given section of track with a given traffic flow, for each type of rolling stock a combination of operating conditions and physical sources may occur. The operating conditions are constant speed, acceleration, braking, curving and stationary operation. The physical sources are rolling noise, impact noise, traction noise, curve squeal in points or curves, broadband or tonal braking noise and aerodynamic noise. The IMAGINE models for each physical source are presented and their relevance for each operating condition is discussed. Some examples of default input data and a brief description of measurement methods are given.

1 Introduction

Within the European project IMAGINE [1], the railway noise model developed in the Harmonoise project [2] has been further elaborated, particularly the source description. This contains several new elements in comparison to existing national prediction schemes, such as the European Interim method for railway noise [3], which is based on the Dutch national prediction method, SRM II [4]. A description of the Harmonoise engineering model is given in [7,8]. The source descriptions for most sources should be considered as preliminary, as little previous research effort was focussed on other sources than rolling noise.

The source description has to be appropriate to cover a variety of situations in which different operating conditions and physical sources can be predominant. At any given location along a railway line, often only a limited number of operating conditions and physical sources are present. Therefore the source model must contain all sources required, especially those that occur in noise sensitive locations.

Firstly the traffic noise model is described, focussing on the combination of operating conditions and physical sources. Then each individual physical source is described. Finally a brief description of measurement methods for acquiring source data is given.

2 Railway 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 \( L_{\text{peq}, \text{rec}} \) due to the traffic flow is determined from energy summation over frequency bands, track segments and source heights:

\[
L_{\text{peq}, \text{rec}} = \sum_{i=1}^{B} \sum_{j=1}^{J} \sum_{h=1}^{N_h} \sum_{i=1}^{I} 10 \log (10^{L_{\text{peq},ijh}/10} + 10^{L_{\text{FA},i}/10} + \ldots) 
\]

with

\[
\Sigma = \text{energy sum: } \Sigma x_i = 10 \log (10^{L_{\text{FA},i}/10} + 10^{L_{\text{FA},i}/10} + \ldots)
\]

\( L_{\text{peq},ijh} \) sound pressure level in frequency band \( i \) due to the contribution from segment \( j \) and source height \( h \) [dB];

\( L_{\text{FA},i} \) 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 \( L_{\text{peq},ijh} \) is determined from the level of sound power per unit length in each segment \( L_{\text{W},ijh} \) due to the traffic flow (see figure 1) with

\[
L_{\text{peq},ijh} = L_{\text{W},ijh} + 10 \log l_{\text{seg}} - A_{\text{total},i} \tag{2}
\]

where

\( L_{\text{W},ijh} \) is the level of sound power per unit length in frequency band \( i \) on segment \( j \) and at source height \( h \) [dB];

\( l_{\text{seg}} \) is the segment length [m];

\( A_{\text{total},i} \) 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 [8].

Five source heights (h) are used to which sound power is allocated (see figure 2).

The level of sound power per unit length \( L_{W} \), for the traffic flow depends on the vehicle emission \( L_{W} \), 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:

\[
L_{W,jh} = \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{p=1}^{P} \left( L_{W_{imp},j} + 10 \log \left( \frac{N_{u,mk}^{l_{u,m}}}{1000v_{mk}} \right) + C_{dir,ph} \right)
\]

with

- \( K \) = number of operating conditions relevant at the segment: 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: 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;
- \( v_{mk} \) = train speed in km/h, for type \( m \) and condition \( k \);
- \( C_{dir,ph} \) = directivity function for each source type \( p \), source height \( h \) and frequency band \( i \). Directivity is in the horizontal plane and is 0 for monopole; for a dipole it is given by:

\[
C_{dir,ph} = 10 \log \left( 2 \cos^{2} \left( \frac{\pi}{2} - \phi \right) \right)
\]

where \( \phi \) 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 \( L_{W,jh} + 10 \log l_{seg} \), and for an individual train or vehicle using \( L_{W_{imp},j} + 10 \log l_{veh} \).

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.

### 3 Source description

#### 3.1 Overview

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).
and can be determined either by calculation or by measurement. The transfer function \( L_{\text{HPR,veh}} \) has the reference unit of sound pressure squared per unit roughness squared, normalised to the axle density \( N_{ax} / l_{veh} \).

Rolling noise is speed dependent and is therefore relevant for the operating conditions constant speed, acceleration, deceleration and curving. Bridge noise is included in the rolling noise source by using a track transfer function at \( h=0 \text{m} \) including the track and the bridge. Defaults for effective roughness and transfer functions are to be published later for common track and wheel types.

### 3.3 Impact noise

Impact noise due to rail joints and other surface irregularities is calculated by introducing an additional roughness term to the formulas (6,7) for rolling noise. Instead of \( L_{\text{tot,i}} \), an equivalent term for impact excitation is used \( L_{\text{impact,i}} \), which is a function of frequency, train speed and of severity and periodicity of the joints. This results in impact noise levels \( L_{\text{peq,impact}}(h=0 \text{m}) \) and \( L_{\text{peq,impact}}(h=0.5 \text{m}) \).

As impact noise is often localised, it has to be taken into account when choosing track segmentation.

### 3.4 Traction noise

Traction noise is strongly dependent on operating conditions and often is predominant during acceleration from standstill, acceleration at speed, low constant speeds, uphill running and standstill. It includes all sources associated with the powertrain and auxiliary components: sources such as diesel engines, fans, generators, electrical converters and other intermittent sources such as compressors, relief valves and others. As each of these 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 [6,9,10,11].

Traction noise is the energy sum of noise due to the powertrain \( L_{\text{pd,cool}} \), cooling fans \( L_{\text{pfan,s}} \) and other (intermittent) sources \( L_{\text{pd,i}} \):

\[
L_{\text{peq,traction}} = L_{\text{pd,cool}} \oplus L_{\text{pfan,s}} \oplus L_{\text{pd,i}}
\]
where
\[
\Sigma \Phi = \text{energy sum: } \Sigma \Phi_x = 10 \lg \left( 10^{11/10} + 10^{2/10} + \ldots \right)
\]

Noise from the powertrain is often approximately proportional to the driveshaft speed \( n_{\text{drive}} \) 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. Especially for locomotives, it is important to apply a sufficiently high load to obtain realistic noise emission levels. A hauled load of at least 10 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:

\[
L_{\text{drive}}(n_{\text{drive}}) = L_{\text{drive,max}}(f_i, (n_{\text{drive,max}}/n_{\text{drive}}))
+ C_{\text{drive}} \lg (n_{\text{drive}}/n_{\text{drive,max}}) \quad (9)
\]

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

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

\[
L_{\text{fan}}(n_{\text{fan}}) = L_{\text{fan,max}}(f_i, (n_{\text{fan,max}}/n_{\text{fan}}))
+ C_{\text{fan}} \lg (n_{\text{fan}}/n_{\text{fan,max}}) \quad (10)
\]

\( L_{\text{fan,max}} \) is determined for a maximum drive speed \( n_{\text{fan,max}} \) (or the nearest feasible speed) and the factor \( C_{\text{fan}} \) is determined from 2 or more operating points. A default value for \( C_{\text{fan}} \) 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 (10) may coincide with formula (9), with \( C_{\text{drive}}=C_{\text{fan}} \).

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

\[
L_{pq,i} = L_{pq,i,+} + 10 \lg (d_q) \quad (11)
\]

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 sources 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 2.

Table 2: default drive shaft speeds for diesel engines and fan shaft speeds for different operating conditions

<table>
<thead>
<tr>
<th>Drive speed ( n_{\text{drive}} )</th>
<th>Fan speed ( n_{\text{fan}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant speed</strong></td>
<td></td>
</tr>
<tr>
<td>( n_{\text{drive, idle}} + )</td>
<td>( n_{\text{fan, min}} + )</td>
</tr>
<tr>
<td>( 0.5(n_{\text{drive,max}}-n_{\text{drive, idle}}) )</td>
<td>( 0.25(n_{\text{fan,max}}-n_{\text{fan, min}}) ) or ( n_{\text{fan, LOW}} )</td>
</tr>
<tr>
<td><strong>Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>( n_{\text{drive, acc}} + )</td>
<td>( n_{\text{fan, min}} + )</td>
</tr>
<tr>
<td>( 0.75(n_{\text{drive,max}}-n_{\text{drive, idle}}) )</td>
<td>( 0.75(n_{\text{fan,max}}-n_{\text{fan, min}}) ) or ( n_{\text{fan, HIGH}} )</td>
</tr>
<tr>
<td><strong>Deceleration</strong></td>
<td></td>
</tr>
<tr>
<td>( n_{\text{drive, dec}} )</td>
<td>( n_{\text{fan, min}} + )</td>
</tr>
<tr>
<td>( 0.75(n_{\text{fan,max}}-n_{\text{fan, min}}) ) or ( n_{\text{fan, HIGH}} )</td>
<td></td>
</tr>
<tr>
<td><strong>Idling</strong></td>
<td></td>
</tr>
<tr>
<td>( n_{\text{drive, idle}} )</td>
<td>( n_{\text{fan, min}} ) or ( n_{\text{fan, LOW}} )</td>
</tr>
</tbody>
</table>

If it is possible to measure traction noise for all required conditions with all relevant sources in operation, then formulas (8)-(10) can be omitted. In that case, source spectra are determined for idling \( L_{\text{peq, idle}} \), acceleration \( L_{\text{peq, acc}} \), constant speed, \( L_{\text{peq, cs}} \), and deceleration \( L_{\text{peq, dec}} \). Measurements on locomotives should be performed with a load of at least 10 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.

3.5 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 2000m 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. So the emission level \( L_{\text{peq, i, squeal}} \) is given as a constant, depending on the track (curve or points) and the vehicle type. The source height is at axle height (0.5m).

Currently proposed defaults for curve squeal are:

\[
L_{\text{peq, curve squeal, point}} = 100 \, \text{dB @ 1kHz, 2kHz} \quad (12)
\]

\[
L_{\text{peq, curve squeal, curve}} = 95 \, \text{dB @ 2kHz, 4kHz} \quad (13)
\]

3.6 Braking noise

Two types of braking noise are relevant for the prediction model as they can produce significant levels: braking at speed, which can produce broadband noise, and braking at lower speeds causing brake squeal.

Braking at speed is most relevant for cast-iron block-braked vehicles, and can be described with a braking noise level at known speed and a speed dependent term:

\[
L_{\text{peq, i, brake}} = L_{\text{peq, i, brake}}(v) + C_{\text{brake}} \lg \left( \frac{v}{v_0} \right) \quad (14)
\]

Brake squeal tends to have a fairly constant level which sets in below a certain braking speed \( v_{\text{squeal}} \), and only occurs for some types of rolling stock. It is given by \( L_{\text{peq, i, brake squeal}}(v) \), for \( v < v_{\text{squeal}} \) a measured quantity. The source height is at axle height (0.5m). Braking noise can also occur at constant speed on a downhill run. Proposed defaults for braking noise are:

\[
L_{\text{peq, i, brake}}(v) = 88 + 30 \lg \left( \frac{v}{80} \right) \quad @800-8000 \, \text{Hz} \quad (15)
\]

(only for cast iron block-braked vehicles) and

\[
L_{\text{peq, i, brake squeal}} = 100 \, \text{dB @ 1kHz} \quad (16)
\]

for \( v < 50 \, \text{km/h} \).

3.7 Aerodynamic noise

Aerodynamic noise tends to be relevant at high speeds, typically above 200 km/h, and therefore it should first be checked whether it is actually required in a given situation. If the rolling noise is characterised by roughness and transfer functions, it can be extrapolated to higher speeds and a comparison can be made with existing high speed noise data to check whether aerodynamic noise is dominant.

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

\[
L_{\text{peq, i, aero}}(h,v) = L_{\text{peq, i, aero}}(h,v_0) + \alpha(h) \lg \left( \frac{v}{v_0} \right) \quad (17)
\]

where \( v_0 \) is a speed at which aerodynamic noise is dominant and \( \alpha(h) \) 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). Some types of rolling stock may have additional sources at other heights.

Proposed defaults for aerodynamic noise are:

\[
L_{\text{peq, i, aero}}(v,h=0.5m) = 63 + 60 \lg (v/80) \quad @20-8000Hz \quad (18)
\]

\[
L_{\text{peq, i, aero}}(v,h=4m) = 65 + 60 \lg (v/80) \quad @4000-5000Hz \quad (19)
\]

4 Measurement methods and other issues

The operating conditions and physical sources can be measured according to the EN ISO 3095 standard, with some exceptions. The measured quantity is always the equivalent sound pressure level over the vehicle transit time, \( L_{\text{peq, Tp}} \) measured at 7.5m. Additional speeds may be required to obtain speed or shaft speed dependency.
coefficients. More details on how to obtain the emission data for traction noise, curve squeal and braking are given in [9]. Proposals for default data for the various noise sources are also given in [9], and further data is to be proposed in the IMAGINE project.

The conversion of data from existing national prediction schemes and the European Interim railway noise prediction model is an issue still to be addressed. The model presented offers a suitable framework to fit the known noise emission of various types of rolling stock to the model by tuning the influence parameters (in particular roughness, transfer functions and traction noise parameters). In some countries, noise emission is given for whole train types including locomotive and wagons. This model can also take this approach into account.

Another issue still to be addressed is application guidelines for the model in practical situations (track segmentation, sources to include, etc.) so as to limit the required modelling effort.

Finally, it should be remarked that not only the quality of source data is important for representative results but also the accuracy of traffic data (types, speeds and numbers of vehicles).

5 Summary

A railway noise model is now available, capable of covering many situations with characteristic noise sources; the parametric approach can take noise control measures such as roughness control and quieter wheel or track designs better into account. In contrast to existing national calculation schemes, the source model is less specific to national rolling stock and tracks, and is based more on a physical description or direct measurement data for each source type.

The separate inclusion of sources such as curve squeal, traction and braking noise will require further assessment in the future, especially in terms of how to apply these in different field situations. Further data collection is required for different types of rolling stock under representative operating conditions to provide a complete set of source data.

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References

[1] IMAGINE Project - www.imagine-project.org