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Railway source models for integration in the new European noise prediction method proposed in Harmonoise

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Abstract

The purpose of the Harmonoise European project is to provide an engineering model for the propagation of road and rail traffic noise which requires, for a better accuracy than existing models, the distinction between source output and propagation. In that context, the purpose of work package 1.2 of Harmonoise is to provide the emission data for railway sources to be implemented in the engineering model for the propagation. The relevant output of the emission data that is useful as input of the propagation calculations is the sound power level of equivalent moving point sources for at most five fixed heights and the associated directivity, both in one-third octave bands. The purpose of Harmonoise is to provide source models based on the most relevant physical parameters which can describe the three main sources: rolling, traction and aerodynamic. A database structure with some examples is also provided as well as guidelines for practical data collection. The paper presents first the main investigations which have been carried out through Harmonoise to provide the source models based on their physical parameters. The paper also presents how the database is organised and linked with the Harmonoise engineering model.

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1. Introduction

The purpose of the Harmonoise project is to provide an engineering model for the propagation of road and rail traffic with the following requirements:

- The engineering model will provide L_{den} values that could be used for noise mapping, for the assessment of annoyed people and effect of action plans (application of European Noise Directive).

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- This model should eliminate inconsistencies of previous models.
- A high scientific quality as well as a good acceptance of the model is required (as accurate as possible, as simple as possible).
- The distinction between source output and propagation should be made.

In that context, the purpose of work package 1.2 is to provide the emission data for railway sources to be implemented in the engineering model for the propagation (developed in work package 3). The railway emission data consist of two things:

- A database file (access format).
- A source model "engine" which consists of the rules to obtain the output from the database. These rules can be integrated in the Harmonoise engineering model.

2. Physical modelling of the sources, relevant parameters to model the sources

The noise emission of trains/tracks must be determined in such a way that the data can be used to make sufficiently accurate predictions of rail traffic noise under different conditions. To make this possible, the train/track system is described as a number of equivalent moving point sources, each with frequency-dependent sound power levels and if necessary, directivity both in the horizontal and the vertical plane. Each type of source is dealt with separately. The strengths of the partial sources must be determined as a function of relevant physical parameters.

A state of the art report has been delivered at the beginning of the project [1]. This document gives an overview of the knowledge on railway sources. The sources which can be considered to be representative of railway emission are the rolling noise, the traction noise and the aerodynamic noise. Other sources can be identified in specific operating conditions like during bridges passing, rail joint passing, curves passing, braking. The parameters that should be controlled to define a railway noise source in particular are given in this document and have been further investigated in the WP1.2.

The main objective of the work carried out in Harmonoise WP1.2 was then to propose a railway source model *based on the relevant physical parameters* allowing the main sources to be described accurately while having in mind that these parameters should be practically assessed. The models for the main sources are described below.

2.1. Rolling noise source

It is now well established [2] that rolling noise is caused by structural vibrations of the wheel, rail and sleepers induced by the combined roughness of the wheel and rail running surfaces. Influences of rail roughness and track composition on rolling noise have been investigated further in the project as described in the following paragraphs. The rolling noise model is illustrated in Fig. 1, and is based on the following parameters:

- The wheel roughness, the rail roughness and the contact filter, these being defined in the wavelength domain. They should be combined and transformed into the frequency domain through the train speed.
- The vehicle and track transfer functions between roughness and sound power.

2.1.1. Wheel and rail roughness

Specific features related to roughness have been studied [3,4]. The main conclusions are as follows.

Previous research on the roughness issue has resulted in several measurement and analysis methods that characterise roughness (excitation) spectrum. Though a review of these methods shows that there is a need for further standardisation, the accuracy of the resulting roughness spectra of the current methods is such that a linear relationship between the roughness spectrum and the noise emission spectrum can be assumed. This

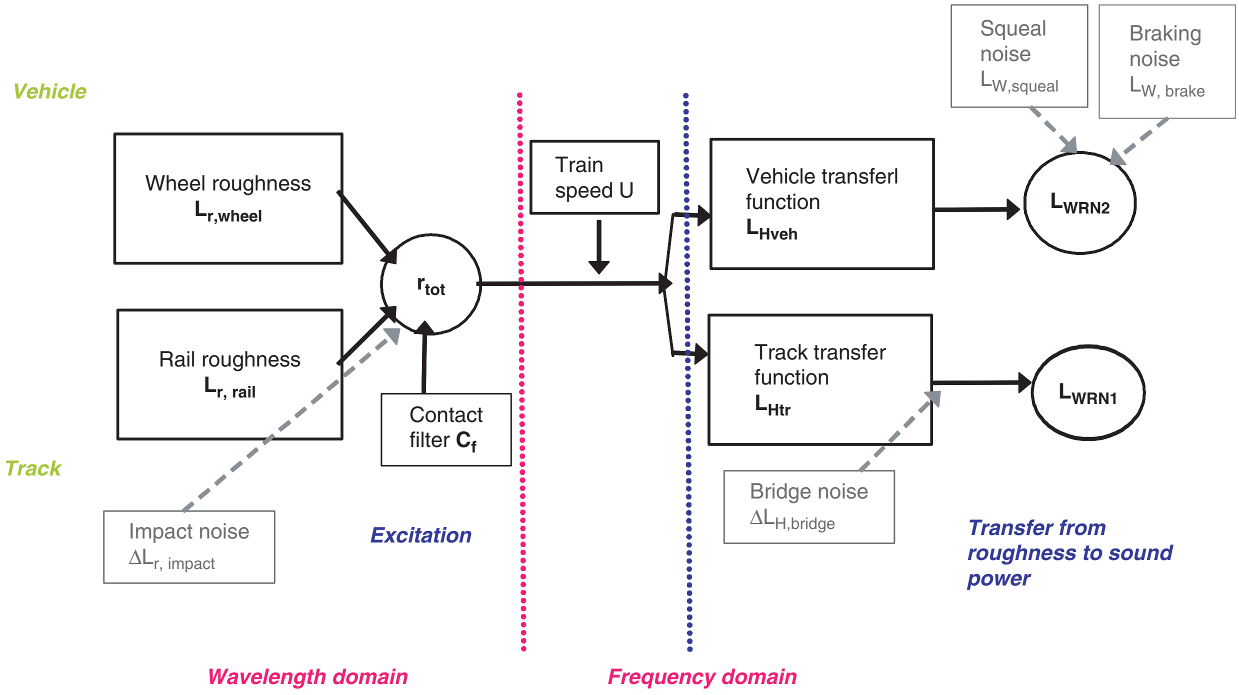

Fig. 1. Physical parameters to provide an accurate rolling noise model.

linearity means that the roughness spectrum can be used directly to calculate the source power spectrum of the railway noise sources.

For wheel roughness, a dependency between the type of braking system and the wheel roughness level is observed. Generally speaking, cast-iron brake blocks generate high wheel roughness and other braking systems do not. A classification can therefore be efficiently based on the braking system of the trains on a network.

A classification system for rail roughness probably cannot be based on external track features, as available statistical data reveals no obvious correlation between rail roughness and such features. It is shown, however, that the spread depends largely on the maintenance regime of the track or network. Specially monitored track (controlled by regular monitoring and grinding) reduces rail roughness where necessary, thereby reducing the spread considerably [5]. This classification problem leaves two basic options for rail roughness in prediction models:

- Using an *average* rail roughness spectrum for the network. The consequence of this approach is that the calculated noise may deviate much (~10 dB) from the actual noise at smooth or corrugated track sections.
- Using *measured* roughness per section of track, by monitoring roughness regularly. This reduces the deviations in the prediction model to approximately ±1 dB. The consequence is that, apart from monitoring, also the database with source data and hence the calculations are to be updated regularly.

For practical reasons, the second option cannot be considered as a recommendation and a compromise between accuracy and practicability needs to be reached by end users.

2.1.2. *Wheel and track transfer function*

Another study has been carried out, using the TWINS software [6], to study the effect of track components on rolling noise emission [7]. The main conclusions are as follows.

The purpose of categorisation as described in Ref. [7] is not to provide a set of default transfer functions to be used for specific track construction. The calculations demonstrate the importance of specifying the track construction types in terms of components. The components turn out to be of influence in different parts of the frequency range. It is demonstrated that the different frequency regions become important at different speeds. As a consequence the influence of the components cannot be neglected.

When the Harmonoise model is used, the track administrator of each EU Member State is responsible for the determination of its own track transfer functions, corresponding to the situations in the country. With the result presented in Ref. [7], a framework for the determination of the transfer functions will be described.

To describe the influence of the track construction and the type of wheel on the total rolling noise, calculations have been carried out using the TWINS program [6]. With the results, categories are defined. The categories, given as sound power levels per one-third octave band, will be put together in a database which serves as an input for the Harmonoise engineering model.

2.1.3. *Source position for rolling noise*

The source positions for rolling noise have been discussed. Two different options can be taken: either all the contributions (wheel and track) are put at the contact position, or the contributions are separated, the vehicle contribution being at the wheel height and the track at the contact position. This last option has be chosen (separate the two contributions), because the details of the source heights can be important in modelling some cases, for example low barriers.

2.1.4. *Data collection for rolling noise*

Measurement methods to obtain the rolling noise parameters and fill in the database can be proposed [8]. They are mainly based on research carried out in previous European projects like STAIRRS (roughness, separation methods). The TWINS software [6] can be used to obtain the vehicle and track transfer functions.

2.1.5. *Other sources*

Additional sources can be considered to describe specific situations such as trains crossing bridges, curve squeal, braking or impact noise (flat wheels or rail joints). These other sources have been reviewed and are proposed to be considered as correction terms of the rolling noise model. These correction terms can be considered at different stages of the model as shown in Fig. 1:

- roughness for the impact noise at the track position,
- track transfer function for bridges, at the track position,
- sound power for curve squeal at the wheel position,
- sound power for braking noise at the wheel position.

2.2. *Traction noise source*

In existing national railway noise prediction schemes, traction noise is covered only rather generally. A description of traction noise sources and parameters has been done in Harmonoise WP1.2 [9]. An overview of available measurement data has been produced and a model has been proposed. The wide variety of noise sources associated with traction noise and their duty cycles can make the assessment of traction noise difficult to generalise. An approach is chosen whereby the most important influence parameters of the main sources are identified:

- For constant speed and acceleration, the powertrain and cooling fan noise can be given as a function of rotational speed. Some recommendations have been given in Ref. [9] for these parameters in average conditions of constant speed, acceleration, standstill/idling and deceleration. In the models for drive (including engine for diesel) and fans, two main effects are included: the level increase and the frequency shift of the spectrum with increasing rpm. The constants C_{drive} and C_{fan} can be obtained through measurements. The fan noise will also require a duty cycle in some cases.
- Other traction noise sources like compressor or blow-off valves or exhaust must be characterised by a constant power spectrum for a given condition, which is allocated a certain duration.

Source heights will have to be chosen based on the known positions of various sources and frequency content at different positions. Source heights may vary considerably for different vehicle types and traction noise needs to be spread over the whole height of the train in the model. Four of the five heights (see Section 3.1 below) could be used to locate a traction noise source. The position at 0.5 m can be used for drive source, the positions at 2 and 3 m for drive, compressor or fan, the position at 4 m for fan and exhaust.

The model of traction noise proposed in Harmonoise certainly needs more investigation to be completely validated.

2.3. *Aerodynamic noise source*

Aerodynamic noise can only be described with very basic parameters. No detailed studies are carried out for this source. The modelling will stay very basic compared with the rolling noise model. An equivalent source that could describe the main aerodynamic physical sources of a French high-speed train (TGV), the bogie area, pantograph and cavity of the pantograph, has been built using background data from SNCF [10]. MAT2S software has been used to test the accuracy of this model and define the best position of the aerodynamic sources. Two possible sources could be considered: one for the bogie area and one for the roof and pantograph. For both these sources, the model consists of:

- reference values of $L_{w,i}$ for a reference speed,
- speed dependence (speed exponent).

The model of aerodynamic noise proposed in Harmonoise is very simple because it is intrinsically impossible to describe the complex physical phenomena like turbulence-induced noise with simple parameters.

2.4. *Directivity*

The horizontal and vertical directivity of a noise source are defined as the corresponding angular distribution of the sound power.

The directivity of railway noise sources cannot be assessed easily by measurements and its relevance to increase the accuracy of the model cannot be simply evaluated. Some suggestions have been made [11] but are not sufficiently validated to be proposed in the final model of Harmonoise.

For calculation of traffic noise levels, it has been proposed to consider only a global coefficient for the horizontal directivity.

3. Railway sources database and link with the Harmonoise engineering model

Fig. 2 presents the end user process for propagation calculations using the Harmonoise engineering model and the integration with the railway emission data. The output of the emission data useful as input for the propagation calculation is:

- The sound power level of *equivalent point sources for five fixed heights* in one-third octave bands for each source height.
- The associated directivity for each source height.

3.1. *Source heights*

Fig. 3 illustrates the different positions that could be used for the calculations. The main criteria which have led to the choice for the source position are the following:

- The rolling noise source is split into track (at $z = 0$) and wheel (at $z = 0.5\,\text{m}$) contributions. It seems that it is more accurate, for example, for treating the case of low barriers.

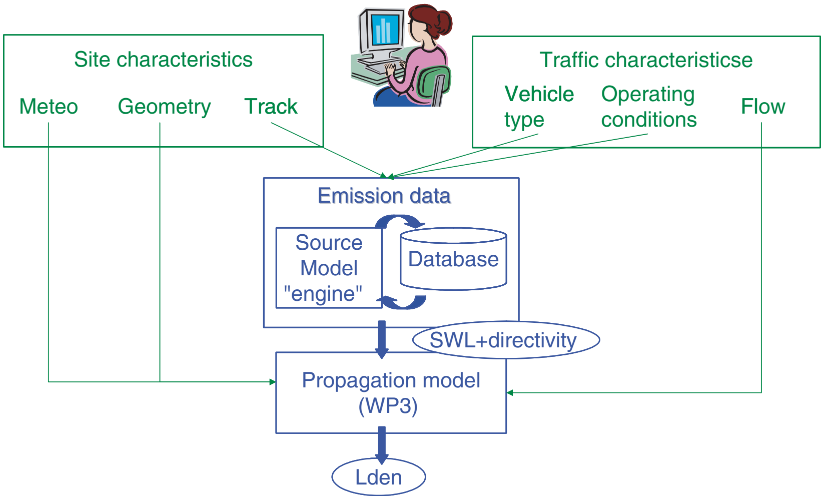

Fig. 2. End user process for propagation calculations.

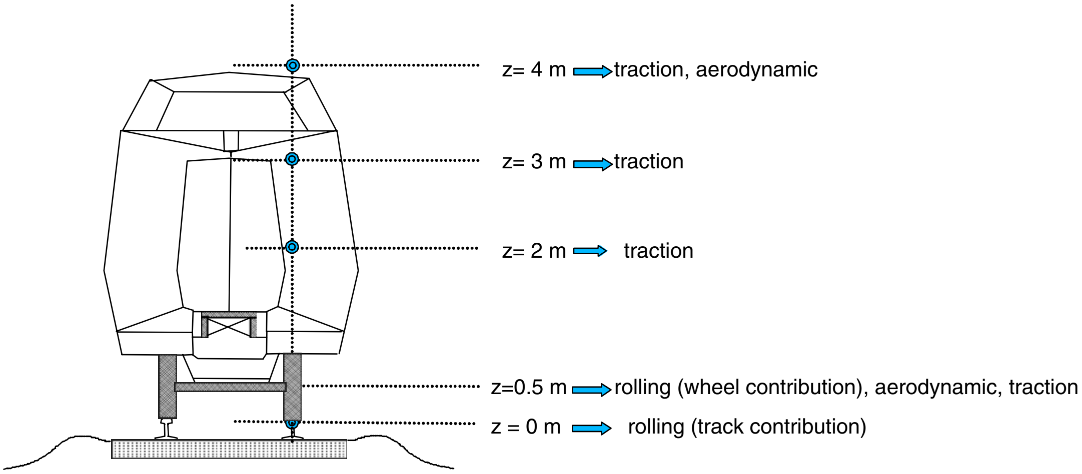

Fig. 3. Source heights.

- The traction noise which includes several physical types of sources (traction motors, auxiliary systems, exhausts…) should be spread over the whole height of the train. Four of the five positions could be used to put a traction noise source, at 0.5, 2, 3 or 4 m.
- The aerodynamic noise is split into two contributions, one contribution for the bogie aerodynamic source which can be put at $z = 0.5$ m and one contribution at 4 m for the equivalent source of the pantograph and, if any, the recess of the pantograph. It has been verified that the aerodynamic source of the bogie area, which is physically closer to 0.8 m can be put at 0.5 m without increasing the uncertainty. It has also been verified that the pantograph noise which is physically closer to 5 m can be put at 4 m without increasing the uncertainty, even with high noise barriers. Some calculations using the NORD2000 model have confirmed this result.

3.2. *"Source model engine"*

For each of these positions, formulae are given to obtain the sound power level. These formulae constitute the "source model engine" which can be integrated into the Harmonoise engineering model. They are given in the appendix.

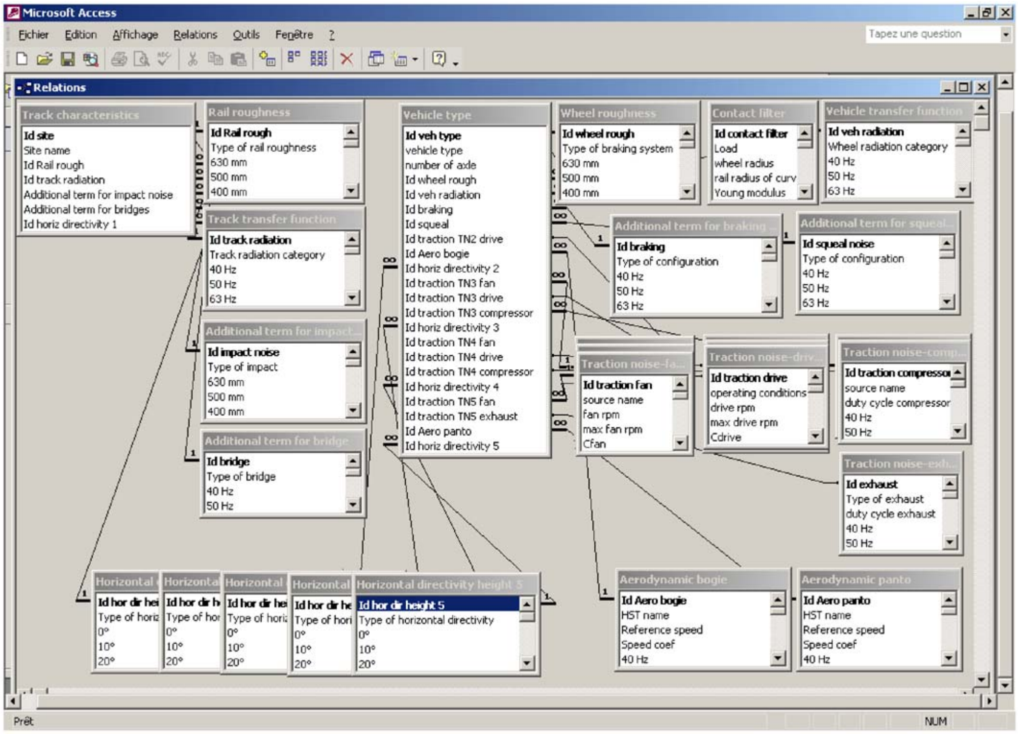

Fig. 4. Database structure.

3.3. Database structure

Fig. 4 illustrates the database structure which is organised around a track description and a vehicle description. The different parameters presented previously are described in the database.

Default classifications or examples are given to help the end-user but when the Harmonoise model is used, each EU Member State is responsible for filling in the database with its own data and the associated accuracy.

4. Conclusions

The work carried out in work package 1.2 of the Harmonoise project has led to a database structure for railway noise sources which can be connected through formulae to the Harmonoise engineering model for propagation calculations. The rolling noise model could be considered as relatively validated because it is close to the modelling principle of rolling noise well known and validated in the TWINS model [6]. The traction noise model is a first proposal that needs to be further investigated and validated. The model of aerodynamic noise proposed is very simple because it is intrinsically impossible to describe the complex physical phenomena like turbulence induced acoustics with simple parameters.

Guidelines to collect the data necessary to fill in the database have been proposed. Each EU Member State will be responsible for filling in the database with the appropriate data, depending on the level of accuracy required by the different types of studies with the Harmonoise engineering model. As an example, average rail roughness could be sufficiently accurate for a global noise map of a country while measuring roughness at a site could offer a better accuracy for specific impact studies.

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Appendix A. Details of the "source model engine"

A.1. Notation

RN	railway noise index (rolling noise + squeal noise + impact noise + braking noise)
AN	aerodynamic noise index
TN	traction noise index
i	index of the frequency, $i =$ one-third octave band i in Hz
f_i	one-third octave band centre frequency
j	wavelength index, $j =$ one-third octave band j in mm
m	vehicle index
n	track index
U	speed (minimum of vehicle speed and track segment speed)
1,…,5	index for the source height
$L_{W1,m,n,i}$	total sound power level at source height 1 for vehicle m and track n, at one-third octave band i (in dB)
$\oplus$	operator symbol for energy summation
N_m	number of axles for vehicle m
$L_{\mathrm{RN}1,m,n,i}$	rolling noise sound power level at source height 1 for vehicle m and track n, at one-third octave band i (in dB)
$L_{r,\mathrm{total},m,n,i}$	total roughness level (wheel + rail + contact filter), for vehicle m and track n, at given speed U, in frequency domain, at one-third octave band i (in dB)
$L_{r,\mathrm{total},m,n,j}$	total roughness level (wheel + rail + contact filter), for vehicle m and track n, in wavelength domain, at one-third octave band j (in dB)
$L_{r,\mathrm{track},n,j}$	rail roughness level, for track n, in wavelength domain, at one-third octave band j (in dB)
$L_{r,\mathrm{wheel},m,j}$	wheel roughness level, for vehicle m, in wavelength domain, at one-third octave band j (in dB)
$CF_{m,n,j}$	contact filter, for vehicle m and track n, in wavelength domain, at one-third octave band j (in dB)
$L_{r,\mathrm{eff,impact},n,j}$	effective equivalent roughness level due to impact for track n, in wavelength domain, at one-third octave band j (in dB)
$L_{r,\mathrm{total},m,n,i}$	total roughness level (wheel + rail + contact filter), for vehicle m and track n, at given speed U, in frequency domain, at one-third octave band i (in dB)
$L_{H\mathrm{tr},n,i}$	transfer function from effective roughness to sound power, for the track n, at one-third octave band i (in dB)
$\Delta_{LH\mathrm{tr},n,i}$	transfer function correction term for bridges, for the track n, at one-third octave band i (in dB)
$L_{H\mathrm{veh},m,i}$	transfer function from effective roughness to sound power, per axle, for the vehicle m, at one-third octave band i (in dB)
$\Delta L_{W,\mathrm{squeal},n,i}$	correction spectrum for squeal noise, for vehicle m, at one-third octave band i (in dB)
$\Delta L_{W,\mathrm{brake},m,i}$	correction spectrum for braking noise, for vehicle m, at one-third octave band i (in dB)
$L_{W\mathrm{TN}2,m,i}$	traction noise sound power at source height 2 for vehicle m, at one-third octave band i (in dB)

$L_{W\text{drive2},m,\text{ndrive},i}$	drive system sound power level at source height 2, for vehicle m, drive rev/min n_{drive}, at one-third octave band i (in dB)
n_{drive}, n_{drivemax}	drive and maximum drive rev/min, which are the diesel motor shaft or gearbox input shaft rev/min and maximum rev/min
C_{drive}	constant for rev/min dependency of drive sound power (can be around 30 for gear noise and for diesel engine noise)
$L_{W\text{fan3},m,n\text{fan},i}$	fan noise sound power at source height 3 for vehicle m, fan rev/min n_{fan}, at one-third octave band i (in dB)
n_{fan}, n_{fanmax}	fan and maximum fan rev/min
C_{fan}	constant for rev/min dependency of fan sound power
dc_{fan}	duty cycle for fans
$L_{W\text{comp3},m,\text{comp},i}$	compressor sound power level at source height 3 for vehicle m, at one-third octave band i (in dB). This source can be characterised for blow-off valves as well
dc_{comp}	duty cycle for compressors
$L_{W\text{exhaust5},m,\text{exhaust},i}$	exhaust sound power level, at source height 5, for vehicle m, at one-third octave band i (in dB)
dc_{exhaust}	duty cycle for exhaust noise
$L_{\text{AN2},m,i}$	aerodynamic noise sound power at source height 2 for vehicle m at one-third octave band i (in dB)
U_{ref2}	reference speed for which L_{ANref2} is given at height 2 (bogie area)
α_2	speed coefficient for aerodynamic noise at height 2 (bogie area)

A.2. Formulae for each source height

The formulae to obtain the sound power level at each source height are detailed here. These formulae constitute the link between the railway source database and the values of the sound power level to be used in the propagation engineering model.

A.2.1. Source height 1, at $z = 0$ m from the rail head: rolling noise (track contribution)

At this position, the only possible source is the track component of the rolling noise. The sound power level at position 1 is then obtained with

$$L_{W1,m,n,i} = L_{W\text{RN1},m,n,i} + 10\log N_m. \tag{A.1}$$

According to the rolling noise model described in Section 2.1, the sound power level of the track part is obtained from the combined roughness and the track transfer function:

$$L_{\text{WRN1},m,n,i} = L_{r,\text{total},m,n,i} + L_{H\text{tr},n,i} + \Delta L_{H\text{bridge},n,i}. \tag{A.2}$$

$L_{r,\text{total},m,n,i}$ is obtained from $L_{r,\text{total},m,n,j}$ following these steps:

- The combined roughness is firstly calculated in the wavelength domain:
- $$L_{r,\text{total},m,n,j} = L_{r,\text{rail},n,j} \oplus L_{r,\text{wheel},m,j} \oplus L_{r,\text{impact},n,j} + CF_{m,n,j}. \tag{A.3}$$
  The classical formulae given in the TWINS manual [12] is used to obtain the contact filter.
- From the speed of the vehicle U, the one-third octave bands frequencies f and the relation $\lambda = U/f$, the corresponding values of λ are calculated. The values of $L_{r,\text{total},m,i}$ are then obtained through an interpolation between values of the two surrounding wavelength one-third octave bands.

A.2.2. Source height 2, at $z = 0.5$ m: rolling noise (wheel contribution)+traction noise (drive)+aerodynamic noise of the bogie area

At this position, the possible sources are the wheel component of the rolling noise, the drive noise and the aerodynamic noise of the bogie area. The sound power level at position 2 is then obtained with

$$L_{W2,m,n,i} = L_{W\text{RN2},m,n,i} + 10\log N_m \oplus L_{W\text{TN2},m,i} \oplus L_{W\text{AN2},m,i}, \tag{A.4}$$

$$L_{W\mathrm{RN}2,m,n,i} = L_{r,\mathrm{total},m,n,i} + L_{H\mathrm{veh},m,i} + \Delta L_{W,\mathrm{squeal},m,i} + \Delta L_{W,\mathrm{brake},m,i}, \tag{A.5}$$

where $L_{r,\mathrm{total},m,n,i}$ is obtained as explained for the rolling noise source at position 1 and via Eq. (A.3)

$$L_{W\mathrm{TN}2,m,i} = L_{W\mathrm{drive}2,m,n\mathrm{drive},i},$$

$$L_{W\mathrm{drive}2,m,n\mathrm{drive},i} = L_{W\mathrm{drive}2,m,n\mathrm{drive\,max},i}(f_i(n_{\mathrm{drive}}/n_{\mathrm{drive\,max}})) + C_{\mathrm{drive}}\log_{10}(n_{\mathrm{drive}}/n_{\mathrm{drive\,max}}), \tag{A.6}$$

$$L_{W\mathrm{AN}2,m,i} = L_{W\mathrm{ANref}2,m,i} + \alpha_2\log_{10}(U/U_{\mathrm{ref}2}). \tag{A.7}$$

A.2.3. Source height 3, at $z = 2\,\mathrm{m}$: traction noise (drive+fan+compressor)

At this position, the possible sources are drive, fan or compressor noise. The sound power level at position 3 is then obtained with

$$L_{W3,m,i} = L_{W\mathrm{TN}3,m,i},$$

$$L_{W\mathrm{TN}3,m,i} = L_{W\mathrm{drive}3,m,n\mathrm{drive},i} \oplus L_{W\mathrm{fan}3,m,n\mathrm{fan},i} \oplus L_{W\mathrm{comp}3,m,\mathrm{comp},i},$$

$$L_{W\mathrm{drive}3,m,n\mathrm{drive},i} = L_{W\mathrm{drive}3,m,n\mathrm{drivemax},i}(f_i(n_{\mathrm{drive}}/n_{\mathrm{drivemax}})) + C_{\mathrm{drive}}\log_{10}(n_{\mathrm{drive}}/n_{\mathrm{drivemax}}),$$

$$L_{W\mathrm{fan}3,m,n\mathrm{fan},i} = L_{W\mathrm{fan}3,m,n\,\mathrm{max},i}(f_i(n_{\mathrm{fanmax}}/n_{\mathrm{fan}})) + C_{\mathrm{fan}}\log_{10}(n_{\mathrm{fan}}/n_{\mathrm{fanmax}}) + 10\log_{10}(dc_{\mathrm{fan}}), \tag{A.8}$$

$$L_{W\mathrm{comp}3,m,\mathrm{comp},i} = L_{W\mathrm{comp}3,m,i} + 10\log_{10}(dc_{\mathrm{comp}}). \tag{A.9}$$

A.2.4. Source height 4, at $z = 3\,\mathrm{m}$: traction noise (drive+fan+compressor)

At this position, the possible sources are drive, fan or compressor noise. The sound power level at position 4 is then obtained with

$$L_{W4,m,i} = L_{W\mathrm{TN}4,m,i},$$

$$L_{W\mathrm{TN}4,m,i} = L_{W\mathrm{drive}4,m,n\mathrm{drive},i} \oplus L_{W\mathrm{fan}4,m,n\mathrm{fan},i} \oplus L_{W\mathrm{comp}4,m,\mathrm{comp},i},$$

$$L_{W\mathrm{drive}4,m,n\mathrm{drive},i} = L_{W\mathrm{drive}4,m,n\mathrm{drive\,max},i}(f_i(n_{\mathrm{drive}}/n_{\mathrm{drivemax}})) + C_{\mathrm{drive}}\log_{10}(n_{\mathrm{drive}}/n_{\mathrm{drivemax}}),$$

$$L_{W\mathrm{fan}4,m,n\mathrm{fan},i} = L_{W\mathrm{fan}4,m,n\,\mathrm{max},i}(f_i(n_{\mathrm{fanmax}}/n_{\mathrm{fan}})) + C_{\mathrm{fan}}\log_{10}(n_{\mathrm{fan}}/n_{\mathrm{fanmax}}) + 10\log_{10}(dc_{\mathrm{fan}}),$$

$$L_{W\mathrm{comp}4,m,\mathrm{comp},i} = L_{W\mathrm{comp}4,m,i} + 10\log_{10}(dc_{\mathrm{comp}}).$$

A.2.5. Source height 5, at $z = 4\,\mathrm{m}$: aerodynamic noise of the pantograph area+traction noise (fan+exhaust)

At this position, the possible sources are aerodynamic noise of the pantograph area and fan or exhaust noise. The sound power level at position 5 is then obtained with

$$L_{W5,m,i} = L_{W\mathrm{TN}5,m,i} \oplus L_{W\mathrm{AN}5,m,i},$$

$$L_{W\mathrm{TN}5,m,i} = L_{W\mathrm{fan}5,m,i} \oplus L_{W\mathrm{exhaust}5,m,i},$$

$$L_{W\mathrm{fan}5,m,n\mathrm{fan},i} = L_{W\mathrm{fan}5,m,n\,\mathrm{max},i}(f_i(n_{\mathrm{fanmax}}/n_{\mathrm{fan}})) + C_{\mathrm{fan}}\log_{10}(n_{\mathrm{fan}}/n_{\mathrm{fanmax}}) + 10\log_{10}(dc_{\mathrm{fan}}),$$

$$L_{W\mathrm{exhaust}5,m,\mathrm{comp},i} = L_{W\mathrm{exhaust}5,m,i} + 10\log_{10}(dc_{\mathrm{exhaust}}), \tag{A.10}$$

$$L_{W\mathrm{AN}5,m,i} = L_{W\mathrm{ANref}5,m,i} + \alpha_5\log_{10}(U/U_{\mathrm{ref}5}).$$

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