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The Harmonoise/IMAGINE model for traction noise of powered railway vehicles

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Abstract

Traction noise is one of the noise sources of powered railway vehicles such as locomotives, electric- and diesel-powered multiple unit trains and high-speed trains. Especially at speeds below 60 km/h and at idling, but also at acceleration conditions for a wide range of speeds, traction noise can be dominant. This is relevant for noise in residential areas near stations and shunting yards, but in some cases also along the line. The other relevant sources are rolling noise, often dominant between 100 and 250 km/h, aerodynamic noise, which can be dominant above 300 km/h, braking noise, curve squeal and impact noise. The braking system can often technically be considered part of the overall traction system, although acoustically it will often have separate noise sources.

In the Harmonoise and IMAGINE EU projects, a generalised prediction model for railway traction noise has been proposed to cover a broad range of powered railway vehicles. The model is one of the prediction modules for overall rail traffic noise, which also covers the other main sources. The traction noise model includes the main operational parameters such as driveshaft speed and power settings, and also takes individual auxiliary components and their duty cycles into account, such as compressors, valves and fans. Source height is included in the model. The level of modelling detail in the many potential traction noise sources has been kept to a minimum, as for the purpose of rail traffic noise prediction it often suffices to model only the dominant sources. Measurement methods are outlined to determine the noise emission spectra, from which extrapolations are made to obtain estimates for different operating conditions.

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1. Introduction

A generalised prediction model for railway traction noise is presented, which has been proposed in the Harmonoise project [1] and modified in the IMAGINE project [2,3] to cover a broad range of powered railway vehicles. The model is one of the prediction modules for overall railway traffic noise, which also covers the other main sources. Traction noise is one of the relevant noise sources of powered railway vehicles such as locomotives, electric- and diesel-powered multiple unit trains and high-speed trains. Especially at speeds below 60 km/h, at idling and acceleration conditions for a wide range of speeds, traction noise can be dominant. With the reduction in rolling noise and the increase in installed power and running speeds, traction noise may in

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some cases even be relevant at medium and high train speeds. Powered vehicles have European noise emission limits from 2004, taking noise due to traction sources into account [4].

Existing noise prediction schemes such as the Dutch RMR 96 model [5], the EU interim methods [6–8] and others tend to mix traction noise together with the other noise sources such as rolling noise, as emission quantities are derived from single-microphone pass-by measurements. The emission source strength is often based on averages for specific train types. A disadvantage of this is that in some situations traction noise may be underestimated and consequently insufficient noise abatement measures might be taken. In the Harmonoise/IMAGINE model, traction noise is covered separately so that it can be described parametrically as an individual source.

Traction noise is relevant for noise in residential areas near stations and shunting yards, but also along the line where trains accelerate or climb a gradient. The other relevant sources are rolling noise, often dominant between 100 and 250 km/h, aerodynamic noise, which can be dominant above 300 km/h, braking noise, which can be dominant at any speed when it occurs, curve squeal and impact noise. The braking system can often technically be considered part of the overall traction system, although acoustically it will often have separate noise sources.

Little background literature on railway traction noise is available, and often not in a form that is suitable for adaptation in a railway traffic noise model. The same is true of measurement data, which do exist, but are often not sufficiently documented with the relevant details such as vehicle parameters or exact operating conditions. The model and methods proposed here are based on a study performed in the Harmonoise project [1] and updated in the IMAGINE project [2,3], in which some available measurement data and measurement methods were assessed.

2. Characteristics of traction noise

2.1. Vehicle types and operating conditions

Traction noise occurs for any type of powered vehicle, and can be concentrated in a single power unit or distributed over two or more power units. Powered vehicles include locomotives and electric or diesel multiple units (EMUs and DMUs) consisting of one or more vehicles and one or more powertrains powered by

- internal combustion engines (ICEs) or other fuel-based power systems, including diesel electric, diesel hydraulic, diesel direct drive systems and others;
- electric drive systems fed externally by an overhead power line or a third rail.

Traction noise can be present, although not always dominant, at all operating conditions. For prediction schemes, traction noise is relevant for acceleration, constant speed, braking and idling conditions, whereby the loading can vary. Noise from the powertrain and auxiliary devices can also contribute to braking noise, for example, from regenerative systems. Noise during idling at standstill is generally dominated by the traction system and auxiliary devices.

The wide variety of noise sources associated with traction noise and their duty cycles can make the prediction of traction noise difficult to generalise. An approach is chosen whereby the most important influence parameters of main sources are identified and a characteristic average operating condition is given for prediction purposes.

2.2. Common traction noise sources

In Table 1 an overview of common traction noise sources is given, with an indication of relevance for noise generation, transmission or radiation, typical operating conditions and main operational influence parameters. Auxiliary and brake-related sources are also included, as they can be linked with the traction system. Other design parameters are not included here as the vehicle design is assumed fixed.

A distinction is made between sources that are actually generating noise, those that transmit noise and those that radiate noise. Noise generation takes place in the powered components such as engine, gearbox and fans.

Table 1
Noise sources from the traction, auxiliary and braking systems

Source	Noise Generation/ Transmission/ Radiation	Relevant for Idling/ Acceleration/ Deceleration/Constant speed	Main operational influence parameters besides design	General relevance for prediction model
Powertrain sources				
ICE exhaust	(G)/T/R	I/A/D/C	Engine shaft rev/min	High
ICE intake	T/R	I/A/D/C	Engine shaft rev/min	High
ICE engine structure	G/T/R	I/A/D/C	Engine shaft rev/min	High
ICE turbocharger	G/T/R	A/C	Turbo shaft rev/min	Medium
Electric motor and generator/ alternator	G/T/R	A/D/C	Engine shaft rev/min and torque	Low
Electric power systems including switching, convertor and other circuitry	G/T/R	I/A (/D/C)	Current or mechanical characteristics	Low
Gear transmission	G/T/R	A/D/C	Input shaft rev/min	Medium
Hydraulic pumps, motors, junctions, valves and piping	G/T/R	I/A/D/C	Pump rev/min and torque	Low
Other types of drive system	G/T/R	I/A/D/C	Shaft rev/min and other	—
Auxiliary systems				
Cooling fans	G/T/R	I/A/D/C	Fan rev/min	High
Ducts	(G) /T/R	I/A/D/C	Fan rev/min	Medium
Cooling inlets	R	I/A/D/C	Fan rev/min	High
Cooling outlets	R	I/A/D/C	Fan rev/min	High
Braking systems				
Compressors	G/T/R	I/A/D (/C)	Compressor rev/min	Medium
Blow-off valves	G/T/R	I/A/D/C	Pressure drop and flow speed	Medium
Brake squeal of wheels	G/T/R	D	Braking force, train speed, friction conditions	High
Brake friction of brake blocks on wheels or brake discs	G/T/R	D	Braking force, train speed, friction conditions	High

Radiation occurs on large surfaces and openings directly linked to the powered components, i.e. inlets, exhaust orifices and cooling vents. Noise transmission occurs between the noise-generating and noise-radiating components. For example, a muffler will transmit noise from the engine to the exhaust orifice, and an electric drive unit may generate and transmit structure-borne noise through the vehicle structure to outside walls, floors or roofing.

Within each of the above-mentioned sources, there may be some other noise generation mechanisms or transmission paths, but this is beyond the scope envisaged here. Therefore, only the main general influence parameters are described. For fans it should be noted that there may be several different fans for various cooling requirements, such as air-conditioning, main cooling tower, motor cooling and others.

For several major sources, the speed of the drive shaft is an important influence parameter. This shaft speed is not always directly linked to the train speed, which is the case for diesel–electric and diesel–hydraulic drives, fans, compressors, generators and other rotating equipment. In these cases, the driveshaft speed depends more on the required power and cooling than the actual train speed. Gear noise may in some cases be directly linked to the train speed if the gear noise is caused by gearwheels on the axles. Sources that are not directly connected to the powertrain may not always be well predictable in terms of timing and duration; for example, the operation of compressors, blow-off valves and forced cooling fans. Their individual sound emission can however be easily quantified by measurement.

Most powertrain-related noise sources depend on the driveshaft speed and power. The sound power level from internal combustion diesel engines will usually have a speed dependence of approximately 30 lg rev/min

[9], where lg is $\log_{10}$. The power dependency at a given drive speed will tend to be around $10\,\lg P_{\mathrm{mech}}$, but as the drive characteristics for any system are strongly coupled, it is proposed to only use shaft speed (rev/min) for prediction purposes.

Fans will tend to have a sound power level speed dependence of about 50 lg rev/min (see, for example, Ref. [9]). Some fans are speed controlled with a variable shaft speed, whereas others are operated at one or two fixed speeds.

Many types of compressors used in trains today can produce significant noise levels, although in newer rolling stock quieter types are also used. Compressors are usually operated at fixed speed for a limited time period.

Some particular electronic components and switching devices will have unique noise characteristics such as only power dependency, but they only need to be taken into account if they are dominant sources. They tend to have strong tonal components either at fixed frequencies or frequencies increasing with load.

Braking may cause high noise levels: friction noise from the wheels or brake discs, brake squeal and blow-off valves are common sources. The duration of these events can be relatively short, but the levels can be high. Braking noise at locations near stations can be of longer duration and even dominant at some locations if all incoming trains are slowing down. Brake friction noise will tend to be broadband at medium and high speeds and last the whole braking cycle. Brake squeal will tend to occur at lower speeds, often quite close to stations; it has a relatively short duration, but can produce high noise levels.

2.3. *Duty cycle of different sources*

Figs. 1 and 2 give qualitative examples of sound level histories of powered vehicles for constant speed and for the deceleration/standstill/acceleration situation. These figures are illustrative and based on observation. The levels are indicative of those for a microphone moving alongside the vehicle. For acceleration and constant speed, the traction noise for diesel powered vehicles can be dominated by engine speed (rev/min), which is related to the power output, not the train speed. The diesel engine shaft speed increases rapidly at acceleration, then slowly reduces again, as shown in Fig. 1. At constant train speed, the power output and shaft speed will tend to vary.

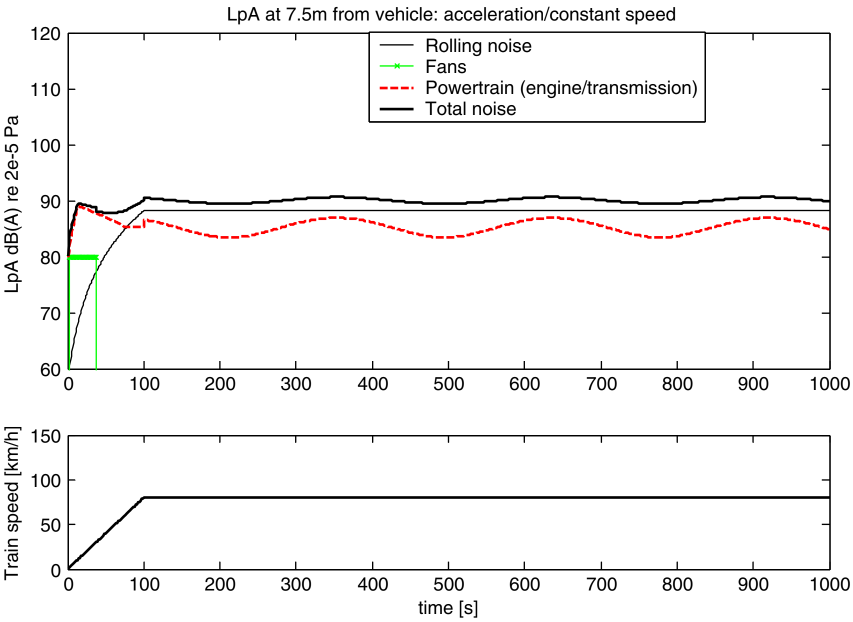

Fig. 1. Indicative noise level time history next to the vehicle for acceleration and constant speed for a diesel-powered locomotive or multiple unit (top). Vehicle speed is indicated in the lower graph. The diesel rev/min increases rapidly at acceleration, and then slowly reduces again. At constant train speed the power output and rev/min can vary.

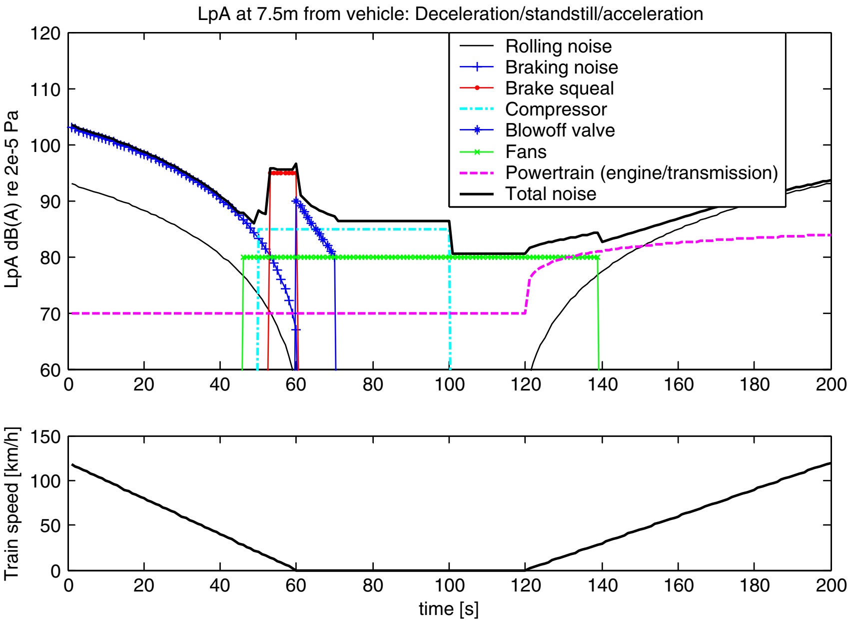

Fig. 2. Indicative noise level time history next to a powered vehicle for deceleration/braking, standstill/idling, and starting/acceleration conditions for locomotives and multiple units.

The actual source strength, timing and duration of each source will depend strongly on particular design and operating conditions. Fig. 2 illustrates that even a source of short duration can still be important for the total level, depending on which part of the level history is included. It also indicates that the most important events can be quantified separately by measuring them together with their duration when they occur.

3. Model for traction noise

3.1. Emission quantities

Railway noise prediction models generally require emission data in terms of a sound power expression. Such data are commonly collected from pass-by measurements using the equivalent sound pressure level $L_{\mathrm{eq,Tp}}$ during the pass-by time of a train T_p (transit time from front to back). All levels and associated quantities in the following can be expressed as spectra in one-third octave or octave bands. The sound power level L_W can be calculated (see Refs. [1,10]) from

$$L_W(f) = L_{\mathrm{eq,Tp}}(f) + 10\,\mathrm{lg}(4\pi r) + A_{\mathrm{excess,avg}}(f) - 10\,\mathrm{lg}((\phi_2 - \phi_1)/l_{\mathrm{veh}}) + \Delta L_W(f), \tag{1}$$

where f is the octave or one-third octave band centre frequency, r is the distance to the microphone, l_{veh} is the vehicle length, and $A_{\mathrm{excess,avg}}$ is the average attenuation between the train and the microphone over the whole view angle, which includes attenuation due to ground absorption and air absorption. The term $\phi_2{-}\phi_1$ is the view angle of the train as seen from the microphone, and for measurement time T_p it can be taken as $\phi_2{-}\phi_1 = 2\,\mathrm{atan}(l_{\mathrm{veh}}/2r)$. $\Delta L_W(f)$ is a directivity correction with total energy integral of unity, which for vehicles with sources distributed over the length can be negligible. Directivity is discussed in more detail in Ref. [10]. Normalisation of Eq. (1) to the train length l_{veh} gives sound power per unit length. Traction noise data can be collected in this way from a train pass-by, but also in some cases from a stationary measurement.

For sources with non-stationary or intermittent behaviour such as compressors, valves and thermally controlled fans, a stationary measurement may be simpler to perform. The duty cycle of the source has to be taken into account in the overall emission. This can be done by correcting for the duty factor $d_i = T_i/T$

representing the fraction of operation time T_i during the total measurement time T:

$$L_{Wdi} = L_{Wi} + 10\lg(d_i), \tag{2}$$

where L_{Wi} is the sound power of source i and L_{Wdi} is the time-corrected sound power level of source i.

Where appropriate, sources can be allocated to a single source height h_j, and if necessary distributed over two or more heights, whereby the total sound power of a given source L_{Wi} must equal the energy sum of partial contributions at each height $L_{W_{ij}}$:

$$L_{Wi} = 10\lg\sum_j 10^{L_{W_{ij}}/10}. \tag{3}$$

The total sound power level L_{Wj} at each source height j for traction noise is the energy sum of the individual sound power levels $L_{W_{ij}}$ for each source i:

$$L_{Wj} = 10\lg\sum_i 10^{L_{W_{ij}}/10}. \tag{4}$$

The default source heights defined in Harmonoise are relative to the rail surface: 0, 0.5, 2, 3 and 4 m. Directivity of traction noise sources can be taken into account in a way similar to rolling noise as most sources are baffled by the vehicle wall structure; they tend to have the strongest radiation in lateral direction. This tends to result in an overall dipole characteristic for a whole train, but is less relevant when determining the sound power for a pass-by.

3.2. Parametric model for drive and fan noise

The model for powertrain and fan noise is based on the following operational parameters:

- powertrain drive rotational speed n_{drive}, which is the diesel motor shaft speed or gearbox input shaft sped (rev/min);
- fan speed n_{fan} of the most dominant fan(s), and overall constants covering the design.

Two main effects are included: the level increase and the frequency shift of the spectrum with increasing rotational speed. For stable constant operating conditions, the sound power of the drive system $L_{W\text{drive}}$ can be predicted in one-third octave bands with:

$$L_{W\text{drive}}(f, n_{\text{drive}}) = L_{W\text{drive},n\text{max}}(f(n_{\text{drive,max}}/n_{\text{drive}})) + C_{\text{drive}}\lg(n_{\text{drive}}/n_{\text{drive,max}}), \tag{5}$$

where $L_{W\text{drive},n\text{max}}$ is the sound power of the drive at maximum rev/min, f is the one-third octave band centre frequency, n_{drive} is the drive rotational speed and $n_{\text{drive,max}}$ is the maximum drive rotational speed. C_{drive} is a constant for rotational speed dependence of drive sound power, and can be around 30 for diesel engine or gear noise. $L_{W\text{drive},n\text{max}}$ and C_{drive} are determined from measurements. Two or more measurements at different engine speeds are required to determine C_{drive}.

For idling conditions, the sound power level might not follow this rule, especially for diesel engines with an exhaust cover or a turbocharger. This situation can result in a different behaviour at idling than under open throttle conditions. In this case, the sound power for idling $L_{W\text{drive,idle}}(f, n_{\text{drive}})$ must be determined separately if it is required for prediction purposes.

For electrically powered vehicles the noise from the drive should be negligible at standstill, possibly with the exception of electromagnetic converter noise. Converter noise and other electrical noise sources will tend not to follow Eq. (5) and should therefore be characterised at representative power settings for acceleration and constant speed.

The sound power from the cooling fans can be predicted in analogy to Eq. (5) with

$$L_{W\text{fan}}(f, n_{\text{fan}}) = L_{W\text{fan},n\,\text{max}}(f(n_{\text{fan,max}}/n_{\text{fan}})) + C_{\text{fan}}\lg(n_{\text{fan}}/n_{\text{fan,max}}), \tag{6}$$

where again $L_{W\text{fan},n\text{max}}$ and C_{fan} (approximately 50) are determined from measurements. The fan sound power is corrected with a duty factor d_i if it is non-continuous in operation.

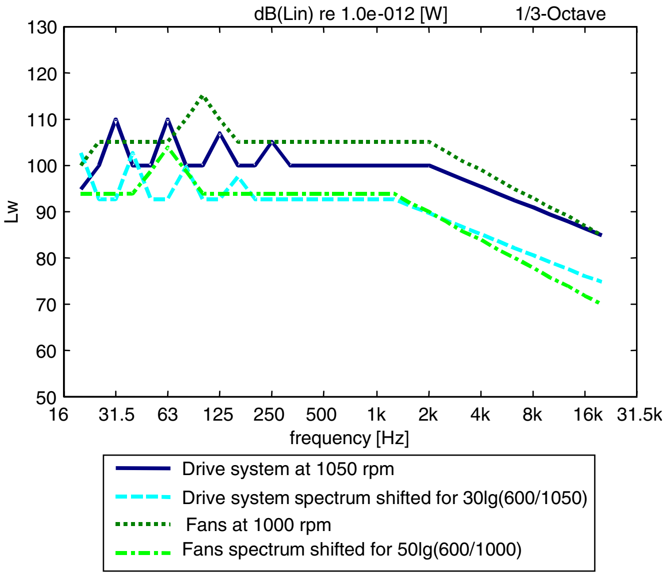

Fig. 3. Simulated sound power spectra for noise of the drive system and fan noise, suitable for acceleration or constant speed pass-by. The spectrum shifts in frequency and level for changing rev/min.

Measurement data of the sound power expressions in Eqs. (5) and (6) can be obtained from sound pressure measurements and converted using Eq. (1).

The model is illustrated here for a vehicle with drive noise and fan noise, at constant speed conditions. It is assumed that the sound power due to the cooling system (one or more fans) is known at a given speed, without influence from other sources such as rolling noise or drive noise. Also, the sound power of the drive system is known at a given engine speed, without influence from other sources such as fans or rolling noise. Using the proposed model, the fan sound power and the drive sound power can be predicted for any speed setting. Increasing speed will increase the level and shift the spectrum accordingly, as illustrated by the simulation in Fig. 3. The model provides an average prediction; the rotational speed dependence may include some irregularity due to airborne or structure-borne resonances. This could be taken into account by measuring at several speeds, which may not be necessary, considering how the data are finally used in the railway traffic noise model.

3.3. Deceleration and braking noise

For deceleration and braking noise a similar approach can be taken. A distinction is made between braking at speed, which may be speed dependent, and brake squeal, which is assumed to be a constant level during low speeds until standstill. There is also a difference to be expected between disc, block and drum brakes, and regenerative braking. Braking noise at speed is given by

$$L_{W\text{brake}}(f, v) = L_{W\text{brake}}(f, v_0) + C_{\text{brake}} \lg(v/v_0), \tag{7}$$

where $L_{W\text{brake}}(f, v)$ is the one-third octave sound power spectrum of the braking system at full braking, v is the train speed and v_0 a reference speed, C_{brake} is a speed dependence factor.

For brake squeal, a short duration constant level, $L_{W\text{squeal}}\,(f)$, is assumed:

$$L_{W\text{dsqueal}}(f) = L_{W\text{squeal}}(f) + 10 \lg(d_{\text{squeal}}), \tag{8}$$

where $L_{W\text{dsqueal}}\,(f)$ is the one-third octave sound power spectrum of brake squeal corrected for duty cycle.

The total deceleration noise $L_{W\text{decel}}(f)$ is the energy sum of braking and brake squeal noise. d_{squeal} is the duty factor.

Table 2
Recommended parameters for traction noise in average conditions of constant speed, acceleration, standstill/idling and deceleration

	Engine rpm for diesel-powered vehicles	Fan rpm for all traction vehicles
Constant speed	50% or nominal rpm for average conditions	25%, nominal rpm, or 'low'
Acceleration	75%	75% or 'high'
Standstill/idling	Idling rpm	50%, nominal rpm, or 'low'
Deceleration	Idling rpm	50% or 'high'

A percentage rpm (shaft speed) means minimum rpm plus percentage of the rpm speed range, i.e. $\text{rpm} = \text{rpm}_{\text{min}} + (\text{rpm}_{\text{max}} - \text{rpm}_{\text{min}})$ *percentage/100.

3.4. Average representative operating conditions

For the purpose of trackside noise prediction at constant speed, acceleration, standstill and deceleration, average representative operating conditions need to be defined. For acceleration, the procedure given in ISO 3095:2001 [11] is available: acceleration from standstill up to 30 km/h, which guarantees significant tractive effort. For locomotives, a realistic load needs to be applied, such as 10 times the locomotive weight, to ensure sufficient tractive effort. For constant speed conditions, the traction system should be engaged, i.e. delivering tractive effort. For deceleration, the traction system will normally not deliver tractive effort, unless regenerative braking is used. At standstill, idling conditions for fans and diesel engines are applicable. In all operating conditions, intermittent sources may be an operational part of the time.

Proposed (estimated) values for diesel engine and fan shaft speeds for each operating condition are given in Table 2. These are of use if the actual shaft speeds at some conditions are not known from measurement or otherwise.

4. Measurement methods

Measurement methods for determining source strength need to be as similar as possible to existing standards such as the exterior noise type testing standard prEN ISO 3095:2001 [11], but there are nevertheless some additional requirements that are briefly outlined here, based on Refs. [2,3,12]. Measurements need only to be performed for the cases that the sources are actually significant, e.g. within 10 dB of the other sources with the highest noise levels.

The site average excess attenuation must be determined, for example, by measurement with a sound source at several positions along the track, or by calculation with an appropriate model. Sound power spectra must be determined for several operating points of the drive and fans, between which spectra can be interpolated. This can be done either at standstill, during acceleration, or at constant speed, whichever is most appropriate. Conversion to other shaft speeds is possible using Eqs. (5) and (6) in Section 3.

At standstill and idling, the sound power for diesel-powered vehicles is determined for drive speeds at 25%, 50%, 75% and 100% of the engine speed range, or at known representative engine speeds. For electrically powered vehicles, the same is done for different fan speeds, or at fixed fan speeds if applicable. The sound power of each individual intermittent source is determined together with the duration of operation. This is only required for significant sources. Heights of each source are determined by their physical position or by special measurement techniques.

For locomotives, appropriate loading is required to achieve representative tractive effort. This is possible by hauling at least 10 times the locomotive weight.

At each of the operating conditions it may not always be simple to separate sources. In this case it is important to identify one or more operating points at which a single source dominates, from which extrapolation is possible.

An acceleration test can be performed to determine sound power under load conditions in the same manner as defined in prEN ISO 3095:2001, with the difference that the L_{eqTp} should be determined instead of $L_{\text{pA}F\text{max}}$. Fan and drive speeds are determined together with the corresponding sound powers, if possible also at maximum driveshaft speed for diesels or maximum fan speed for electrically powered vehicles.

In the constant speed test, 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 braking and deceleration, measurements are required for maximum speed, the medium speed range and at low speeds, sufficient to distinguish braking friction noise and low speed brake squeal. The sound power should be determined from the L_{eqTp}.

The above measurement procedures should be considered as proposals, which could in future be adapted or improved based on further experience.

5. Conclusions

A model for the prediction of railway traction noise has been proposed, which takes the main types of noise source associated with traction, auxiliary and braking systems into account. Both continuous and intermittent sources are included. Average operating conditions for powertrain drive and fans are suggested to obtain representative source emission data. Additional measurements are required in relation to the prEN ISO 3095:2001 standard to determine source emission. Both proposed model defaults and measurement methods will require further validation from more intensive usage in the future.

Acknowledgements

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References

[1] M.G. Dittrich, F. de Beer, X. Zhang, WP1.2 Rail sources—modelling of railway traction noise for input to rail traffic noise models, *Harmonoise Report Ref. No. HAR12TR-030710-TNO02*, 2003.

[2] M.G. Dittrich, IMAGINE Work Package 6—IMAGINE railway noise source model, measurement protocol and default source data, *IMAGINE Report No. IMA6TR-050112-TNO01*, January 2005.

[3] M.G. Dittrich, IMAGINE Work package 6—assessment of railway traction noise model, *IMAGINE Report No. IMA6TR-050225-TNO02*, February 2005.

[4] TSI Noise for conventional rail, *Draft TSI*, AEIF, Brussels, 16 June 2004.

[5] Reken-en Meetvoorschrift Railverkeerslawaai '96, Ministerie Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 20 November 1996 (Dutch railway noise prediction scheme 1996).

[6] European Directive: Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.

[7] European Commission: Commission Recommendation 2003/613/EC of 6 August 2003 concerning the guidelines on the revised interim computation methods for industrial noise, aircraft noise, road traffic noise and railway noise, and related emission data.

[8] Akron/Wölfel et al., Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping: railway noise—description of the calculation, Wölfel consortium 2001.

[9] R.G. White, J.G. Walker (Eds.), *Noise and Vibration*, Ellis Horwood, 1986.

[10] X. Zhang, To evaluate the sound power level from the measured LAeq of a passing-by vehicle, *Harmonoise Memorandum*, *Draft Technical Report*, *Document Ref. HAR1TR-021204-SP04*, May 2004.

[11] prEN ISO 3095: 2001, Railway applications—acoustics—measurements of noise emitted by railbound vehicles.

[12] M.G. Dittrich, M.H.A. Janssens, Voorstel voor een Nederlands typekeuring-meetvoorschrift voor geluid van railvoertuigen (proposal for a Dutch type test protocol for rail vehicle noise), *TNO Report No. HAG-RPT-000081*, July 2000.