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LETTERS TO THE EDITOR

RAILROAD SOUND POWER LEVEL

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1. INTRODUCTION

To predict train noise, the spectrum of the sound power level has to be known. Within 200 m mostly ground effect and air absorption modify geometrical divergence of train noise. Both depend upon the sound power spectrum. Noise generated by a train moving with a steady speed, is assessed by the sound exposure level. The method of the sound power spectrum determination is proposed and validated.

Directive of the European Parliament [1] recommends the day–evening–night level, L_{den}, as an environmental noise indicator. Its definition is as follows,

$$L_{den} = 10\log\left(\frac{1}{24}(12\times 10^{0\cdot 1L_1} + 4\times 10^{0\cdot 1(L_2+5)} + 8\times 10^{0.1(L_3+10)})\right), \tag{1}$$

where L_1, L_2 and L_3, represent the equivalent continuous A-weighted sound pressure level, L_{AeqT}, for day $T_1 = 12$ h (7:00–19:00), evening $T_2 = 4$ h (19:00–23:00), and night $T_3 = 8$ h (23:00 − 7:00) respectively.

The A-frequency weighting (− 16·1, − 8·6, − 3·2, 0·0, + 1.2, and + 1·0 dB) is assigned to the octave frequency bands: 125, 250, 500, 1000, 2000 and 4000 Hz.

If E_{Ai} is the A-weighted sound exposure of a train belonging to the ith category and N_i is the number of the ith category trains passing the receiver during the time interval, T, then,

$$L_{AeqT} = 10\log\left(\frac{1}{Tp_0^2}\sum_{i=1}^{m} N_i E_{Ai}\right), \quad p_0 = 20\mu\text{Pa}, \tag{2}$$

where m denotes the number of train categories (e.g., for Inter City, passengers, and freight trains, one gets $m = 3$).

For each train,

$$E_A = \sum_n E_{An}, \tag{3}$$

where summation runs over frequency bands, and

$$E_{An} = \int_{-\infty}^{+\infty} p_{An}^2\,\mathrm{d}t, \tag{4}$$

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is the corresponding A-weighted sound exposure. Here p_{An}^2 denotes the A-weighted squared sound pressure.

The comparison of the railway noise prediction models has been made by Leeuwen [2]. In each case, the sound power level has to be known. The objective of this paper is the method of train sound power spectrum determination.

2. METHOD

To model a train as a homogeneous line source of length, l, one introduces the concept of the unit length line source. Such a source is characterized by the A-weighted sound exposure, $\tilde{E}_{An}$, and the A-weighted squared sound pressure in the nth frequency band, $\tilde{p}_{An}^2$. Homogeneity of the line source yields (equation (4)),

$$E_{An} = l\,\tilde{E}_{An}, \tag{5}$$

where l is the length of entire train, and

$$\tilde{E}_{An} = \int_{-\infty}^{+\infty} \tilde{p}_{An}^2\,\mathrm{d}t. \tag{6}$$

Let us introduce two angles, φ and ϑ, in the horizontal and vertical plane respectively. The former represents the angle between the perpendicular to the line source and the source–receiver direction, SO (see Figure 1). The latter represents the angle between the normal to the ground and the line connecting the incident point with the receiver, RO (see Figure 2).

Assuming that the power unit generates much less energy than the rest of the train, one can write,

$$\tilde{p}_{An}^2 = P_{An}\rho c\,\frac{\Theta_n(\varphi)}{d^2}\,F_n(d, h, H, \ldots), \tag{7}$$

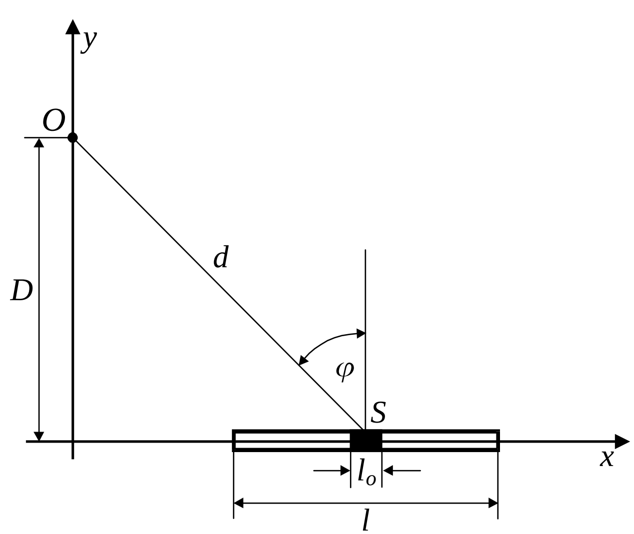

Figure 1. Source–receiver geometry in the horizontal plane.

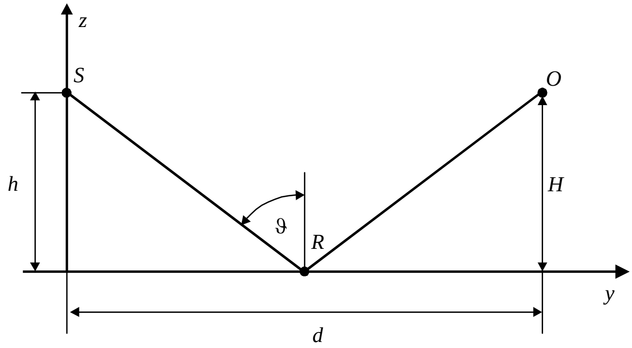

Figure 2. Source–receiver geometry in the vertical plane.

where ρc is the air specific impedance. P_{An} represents the A-weighted sound power of the unit length line source in the nth frequency band and the function $\Theta_n(\varphi)$ encompasses radiation directivity of both: rolling and aerodynamic noises. For the former, the dipole–type model is usually applied, $\Theta_n \approx \cos^2 \varphi$. In the present paper, the explicit form of $\Theta_n(\varphi)$ is not needed. The ratio $\Theta_n(\varphi)/d^2$ accounts for geometrical divergence. The function $F_n(d, \dots)$ describes the excess attenuation caused by ground effect, atmospheric absorption, turbulence, and the other wave phenomena in the nth frequency band [3, 4] Taking into consideration the ground effect, attenuation and turbulence, the explicit form of $F_n(d, \dots)$ can be found in reference [5].

For $d \to 0$ (see Figure 2), the ground reflection plays the major role beneath the train and near the track. Thus, when the receiver is close to the track (e.g., $D = 25$ m, see Figure 1), the excess attenuation for the nth frequency band can be approximated by a single number,

$$\lim_{d \to 0} F_n(d, \dots) = \beta_n. \tag{8}$$

For example for the hard surface, the noise reflection beneath the source is described by $\beta_n \approx 2$.

In the general case, equation (7) takes the form,

$$\tilde{p}_{An}^2 = \tilde{P}_{An} \rho c \frac{\Theta_n(\varphi)}{d^2} \tilde{F}_n(d, h, H, \dots), \tag{9}$$

where $\tilde{P}_{An} = \beta_n P_{An}$ is the power spectrum modified by the ground close to the track and the normalized excess attenuation,

$$\tilde{F}_n(d, h, H, \dots) = \frac{F_n(d, h, H, \dots)}{\beta_n}, \tag{10}$$

where

$$\lim_{d \to 0} \tilde{F}_n(d, \dots) = 1. \tag{11}$$

Usually, the train noise prediction schemes provide both $F_n(d, h, H, \dots)$ (equation (7)) and β_n (equation (8)). The function $\tilde{F}_n(d, h, H, \dots)$ is supposed to be known in the present study.

If the measurements are carried out close to the track, $d \to 0$, then the normalized excess attenuation can be neglected: $\tilde{F}_n(d, \dots) \approx 1$ (equation (11)). Consequently, the inequality,

$$10 \log \frac{F_n(d^*, h^*, H^*, \dots)}{\beta_n} < \Delta L, \tag{12}$$

determines the track-receiver geometry (d^*, h^*, H^*) and the permissible error of the noise prediction (e.g., $\Delta L = 1{\cdot}0$ dB). Therefore, close to the track, $D = 25$ m, the result of geometrical divergence in the horizontal plane is given by (equations (9), (11)),

$$\tilde{p}^2_{An,\,div} \approx \tilde{P}_{An} \rho c \frac{\Theta_n(\varphi)}{d^2}. \tag{13}$$

In a flat and open space, for the train moving with steady speed V along a straight line the sound exposure for the unit length line source (equation (6)) can be calculated by the integral between the limits, $\varphi_1 = -\pi/2$, and, $\varphi_2 = -\pi/2$ (see Figure 1 and reference [6]),

$$\tilde{E}_{An} = \frac{D}{V} \int_{-\infty}^{+\infty} \frac{\tilde{p}^2_{An}(\varphi)}{\cos^2 \varphi} \, \mathrm{d}\varphi. \tag{14}$$

Close to the track (e.g., $D = 25$ m), geometrical spreading prevails and equations (13) and (14) yields,

$$q_n = \int_{-\pi/2}^{+\pi/2} \frac{\Theta_n(\varphi)}{\cos^2 \varphi} \, \mathrm{d}\varphi. \tag{15}$$

Finally, the A-weighted sound exposure in the nth frequency band, i.e., the noise from the whole line source of length l, is described by,

$$E_{An,\,div} \approx \frac{P^*_{An} \rho c}{DV} l, \tag{16}$$

where the A-weighted sound power of the unit length line source is modified by the ground reflection, β_n (equation (8)), and directivity, q_n (equation (15)),

$$P^*_{An} = \beta_n q_n \tilde{P}_{An}. \tag{17}$$

The definition of the sound exposure level,

$$L_{AE} = 10 \log \frac{E_A}{p_0^2 t_0}, \; t_o = 1\mathrm{s}, \tag{18}$$

with the definition of the overall A-weighted sound power level,

$$L_{WA} = 10 \log \frac{\hat{P}_A}{P_0}, \; P_0 = 10^{-12}\, W, \tag{19}$$

enables one to find relationship between L_{AEn} and L_{WAn} (equation (16)),

$$L_{WAn} = L_{AEn} + 10\log\left(\frac{DVt_0}{ll_0}\right). \tag{20}$$

Here, the A-weighted sound power level in the nth frequency band,

$$L_{WAn} = 10\log\frac{P^*_{An}}{P_0}. \tag{21}$$

The sound exposure level is the noise descriptor preferred by ISO [7]. Measurements of L_{AEn}, with the known perpendicular distance, D, train speed, V, and length, l, gives the spectrum of the A-weighted sound power of the unite length line source, P^*_{An} (equations (20), (21)). Then the total A-weighted sound power is, given by

$$P^*_A = \sum_n P^*_{An}. \tag{22}$$

3. MEASUREMENTS

The measurements of the sound exposure levels, L_{AEn}, were carried out at the Poznań–Berlin train line, approximately 30 km west from the terminal in Poznań. The weather was fair with partly cloudy sky. There was weak wind and the average temperature of the air was about 20°C. The flat area of grassland was open, without buildings, trees or any other reflecting and scattering objects nearby. Noise was produced by three types of trains (Inter City, passenger and freight trains) which passed at a steady speed on an embankment of height, h, of about 1 m. The track was straight and level, and the rails were free from any discontinuities and corrugations and laid on wooden sleepers. The microphone was at a perpendicular distance, D, of 25 m from the track centre at the height, H, of 1·2 m.

Making use of equations (19)–(22), we arrived at the dependence of the A-weighted sound power level upon the train speed, V (Figures 3–5): as the speed V increases, the sound power

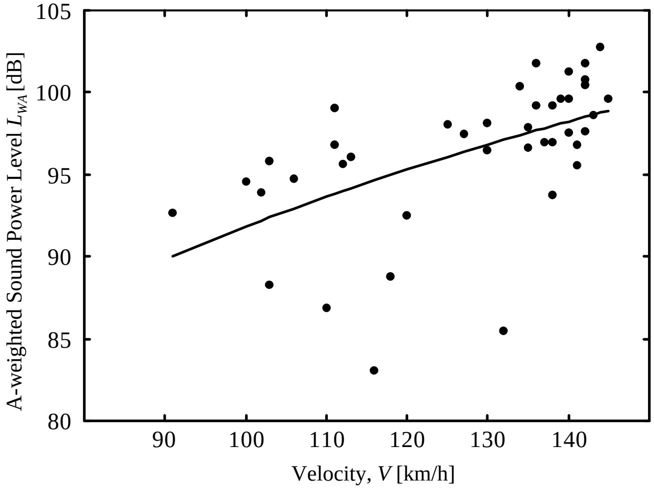

Figure 3. A-weighted sound power level, L_{WA}, for Inter City trains.

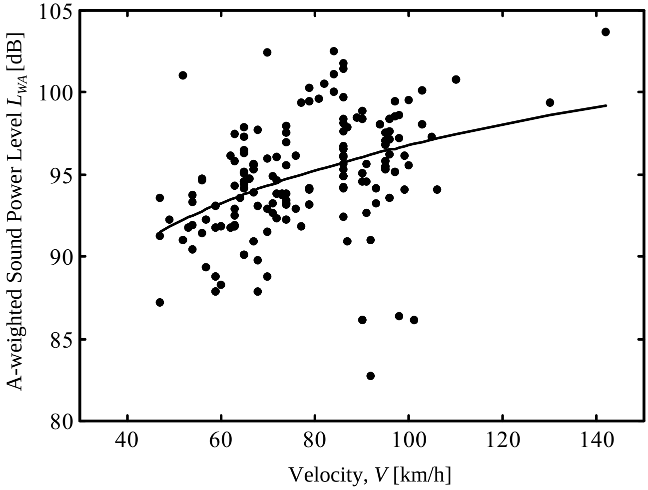

Figure 4. A-weighted sound power level, L_{WA}, for passengers trains.

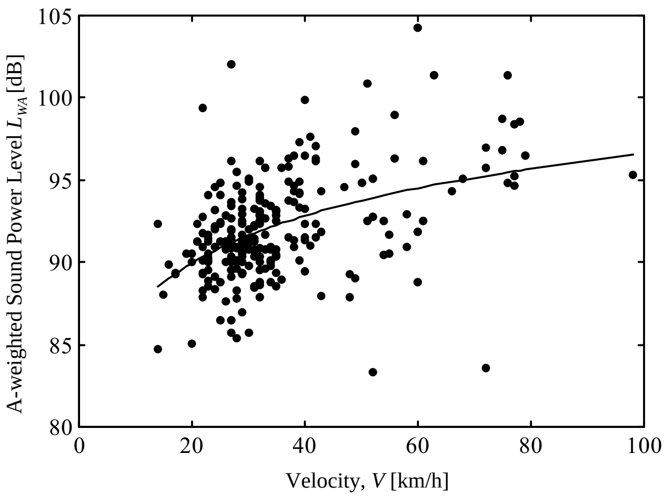

Figure 5. A-weighted sound power level, L_{WA}, for freight trains.

increases as well:

$$L_{WA} = A \log_{10}\left(\frac{V}{V_0}\right) + B, \tag{23}$$

where $V_0 = 1$ km/h. The constants A, B, the correlation coefficient, and the range of train velocities, V_{min}–V_{max}, are presented in Table 1.
The major factors causing spread of L_{WA} is type of breaking employed: discs or treads.

For the average train speed, 127·5 km/h (Inter City-), 78 km/h (passengers-), and 35·3 km/h (goods train), the referenced A-weighted sound power spectrum (equations (19, 21))

$$\Delta L_{WAn} = L_{WAn} - L_{WA} \tag{24}$$

are shown (Figure 6). The maximum at 1600 Hz should be noted.

TABLE 1

The constants A, B (equation (23)), correlation coefficient, and velocity range for each category

Train category	Constants		Correlation coefficient	Velocity range
	A	B		(km/h): V_{min}–V_{max}
Inter City	44·0	3·8	0·5	91–145
Passengers	16·0	67·7	0·4	47–142
Goods	9·5	77·6	0·4	14–98

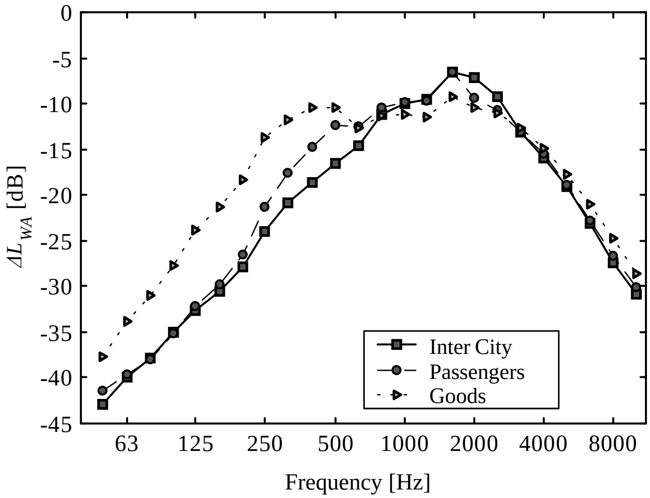

Figure 6. The referenced A-weighted sound power spectrum for Inter City, passenger and freight trains.

A comparison of some spectra for train noise has been given in reference [8]. They are, in general, accordance with the data obtained in the present study (Figure 6).

The sound power level of a unit length line source (per unit length), L_{WAn}, was proposed as an indicator of the noise emitted by trains [9].

4. NOISE PREDICTION

The measurements of the sound power spectrum, L_{WAn}, at the input data point ($D = 25$ m) makes possible prediction of the day–evening–night level, L_{den}, far away from the track ($D > 25$ m).

To calculate, L_{den}, first we write the instantaneous horizontal distance, d, as a function of perpendicular distance and the instantaneous horizontal angle: $d = D/\cos\varphi$ (Figure 1). The excess attenuation, $\hat{F}_n(\varphi) = \hat{F}_n(D/\cos\varphi, h, H, \dots)$ (equation (10)), peaks when the train is opposite to the receiver, $\varphi = 0$ and $d = D$ (Figure 1),

$$\max(\hat{F}_n) = \hat{F}_n(D, h, H, \dots). \tag{25}$$

Because the A-weighted squared sound pressure in the nth frequency band (equations (9), (13)),

$$\tilde{p}^2_{An} = \tilde{p}^2_{An,\ div}(\varphi)\ \tilde{F}_n(D/\cos\varphi, \dots), \tag{26}$$

the modified mean value theorem of integral calculus [10],

$$\int_{-\pi/2}^{+\pi/2} p(\varphi)F(\varphi)\mathrm{d}\varphi \approx F(0)\int_{-\pi/2}^{+\pi/2} p(\varphi)\,\mathrm{d}\varphi \tag{27}$$

yields the A-weighted sound exposure far away from the track (equations (14)–(16), (25), (26)),

$$E_{An} \approx E_{An,\, div}\hat{F}_n(D, h, H, \dots). \tag{28}$$

Combining equations ((16), (18), (28)) one arrives at the sound exposure level for the nth frequency band,

$$L_{AEn}(D) = L_{WAn}(V) + 10\log\left(\frac{ll_o}{DVt_o}\right) + A_n(D), \tag{29}$$

where the excess attenuation,

$$A_n = 10\log(\hat{F}_n(D, H, h, \dots)). \tag{30}$$

When studying noise propagation within 200 m (in the neutral atmosphere without temperature- and wind-refraction) ground effect (subscript gr) and atmospheric absorption (subscript at) becomes the most important factors. Using the excess attenuation model by ISO [11], one can write,

$$A_n = -A_{atn}(D) - A_{grn}(D). \tag{31}$$

Taking all frequency bands together (equations (29), (31)), one gets,

$$L_{AE}(D) = L_{WA}(V) + 10\log\left(\frac{ll_o}{DVt_o}\right) - A(D), \tag{32}$$

where the resultant excess attenuation,

$$A = 10\log\left(\sum_n 10^{0\cdot 1\Delta L_{WAn}}\, 10^{-0\cdot 1(A_{atn}+A_{grn})}\right). \tag{33}$$

Here n runs over frequency bands.

Note that the numerical value of A depends upon the relative sound power spectrum, ΔL_{WAn} (equation (24)). The ISO model [11] provides the explicit form of the functions $A_{grn}(D)$ and $A_{atn}(D)$.

5. VALIDATION TEST

To validate the method of sound power determination (section 2) we performed the simultaneous measurements of the sound exposure level, L_{AEn}, for each train at the distance $D = 200$ m, and the height $H = 1{\cdot}2$ m. Taking the embankment height $h = 1{\cdot}0$ m, the excess attenuation, A_n (equation (31)), was calculated from the ISO method [11]. Then, applying the relative sound power spectrum, ΔL_{WAn} (Figure 6), we calculated the resultant excess attenuation (equation (33)): $A_1 = -8{\cdot}8$ dB (Inter City), $A_2 = -8{\cdot}6$ dB (passenger train), $A_3 = -8{\cdot}3$ dB (freight train). The differences between A_1, A_2 and A_3, are so small that we used the average for all three categories, $A = -8{\cdot}6$ dB. Later, for the measured velocities, the A-weighted sound power, L_{WA}, for each train was found (equation (23) and Table 1). Finally,

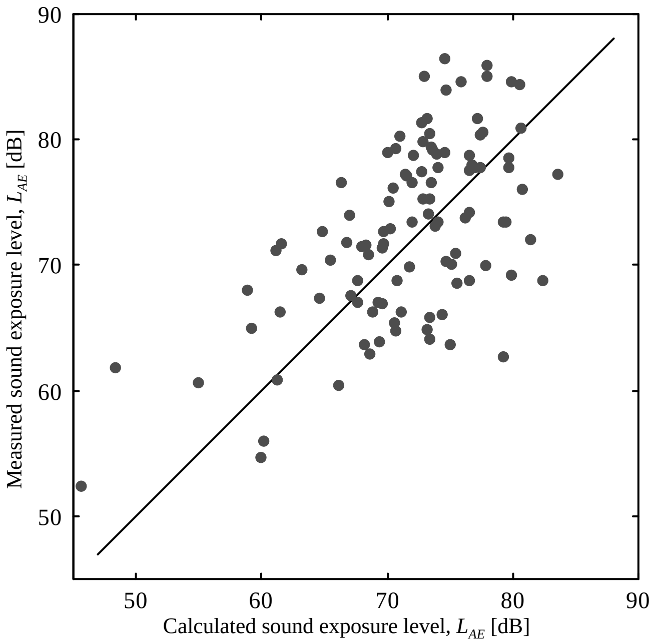

Figure 7. Sound exposure level predicted using equation (32) versus measured sound exposure level.

from the right-hand side of equation (32) we calculated the sound exposure level, $L_{AE}^{(c)}$. The result of measurements, $L_{AE}^{(m)}$, and calculation, $L_{AE}^{(c)}$, for each train are shown in Figure 7. The diagonal line indicates the ideal relationship between two levels for which prediction corresponds exactly to the measurements. The difference $\Delta L_{AE} = L_{AE}^{(m)} - L_{AE}^{(c)}$, ranges from, $-13{\cdot}4$ to $16{\cdot}6$ dB. The mean error ($\Delta L_{AE} = 1{\cdot}0$ dB) for 106 measurements indicates the underestimation.

6. CONCLUSIONS

When the relative sound power spectrum, ΔL_{WAn}, is known (section 3), the wayside sound exposure level, L_{AE}, for each train can be calculated (equations (32), (33)). The method of determining ΔL_{WAn} presented here has been developed under the following assumptions:

- Train is moving with steady speed along a straight, level, and continuous track.
- Train is modelled by a continuous set of unit length line sources.
- One channel measurement of sound pressure level is performed at the site of interest (e.g., $D = 25$ m).
- The ground surface is plane, homogeneous, without interfering objects nearby.
- Only ground effect and atmospheric absorption modify the geometrical spreading.

A comparison of the measured and calculated results (Figure 7) indicates that the method of sound power spectrum determination (section 2) works.

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