Representative spectrum of road traffic noise

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The representative spectrum of traffic noise is expressed in terms of the normalized A-weighted sound pressure level, δL_n . Assuming that the traffic noise annoyance is measured by the time-average sound level, the dependence of δL_n upon the traffic speed and the percentage of heavy vehicles has been derived. For traffic without heavy vehicles, an increase in traffic speed causes δL_n to decrease at low frequencies. The presence of heavy vehicles destroys the dependence of δL_n upon the traffic speed and may increase the value of δL_n a few decibels at low frequencies.

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1. INTRODUCTION

In studying the problem of traffic noise generation, it is convenient to model a stream of cruising vehicles (*i.e.* lane of a road) as a single source. Particularly, the noise spectrum of such a source is useful for noise barrier investigation.¹⁻⁴⁾ Most recently, a noise spectrum, based on measurements taken in various European countries and reviewed by the noise barrier standards committee (CENTC 226/WG6/TG1), has been introduced.⁵⁾ This spectrum, in octave bands, is shown in Fig. 1. Its definition can be given by,

$$\delta L_n = L_{pn} + \Delta L_n - L_{pA}, \quad (1)$$

where L_{pn} expresses the sound pressure level in the n -th frequency band, L_{pA} denotes the A-weighted sound pressure level, and $\Delta L_n = -16, -9, -3, 0, +1, +1$ are the A-weightings, taken for octave bands that are characterized by their central frequencies, $f_n = 125, 250, 500, 1,000, 2,000$ and $4,000$ Hz. The quantity defined by Eq. (1) is called the normalized A-weighted sound pressure level. In view of its definition and the definition of the

A-weighted sound pressure level,

$$L_{pA} = 10 \log \left\{ \sum_n 10^{(L_{pn} + \Delta L_n)/10} \right\}, \quad (2)$$

the problem posed in this paper can be formulated as the following question: what are representative values of the sound pressure level of traffic noise, L_{pn} ? Road traffic consists of vehicles belonging to different types. It has been accepted to assume that there are either two or three main categories of vehicles, such as light, medium, and heavy vehicles. The noise generated by a vehicle on a road is a function of its operation mode and the road's surface. When the vehicle is cruising with steady speed V , both L_{pn} and L_{pA} are related to V .

Therefore, we expect the normalized A-weighted sound pressure spectrum, δL_n (Eq. (1)), to be a function of traffic speed, V , as well. However, L_{pn} for a light and heavy vehicles are not the same (Fig. 2): $L_{pn}^{(1)} \neq L_{pn}^{(2)}$.

Although it may be intuitive to use the arithmetic mean, $[L_{pn}^{(1)} + L_{pn}^{(2)}]/2$, to get the representative sound pressure spectrum, L_{pn} , we must use an alternate method, as the noise contributions due to light and heavy vehicles are not identical. It arises from the relative proportion (mix) of both categories, which depends on the day, the lane of a highway, *etc.*

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Fig. 1 The normalized A-weighted sound pressure spectrum for European traffic noise.⁵⁾

Fig. 2 Sound pressure level for a light and heavy vehicle, $L_{pn}^{(1)}$, $L_{pn}^{(2)}$ measured 1.2 m above the ground at a distance of 15 m, while the speed of cruising is $V=88$ km/h.⁶⁾

Moreover, the acoustic power of a light vehicle is considerably less than that of a heavy vehicle.

Before we show how to calculate the representative spectrum, we make use of the definition of the sound pressure level and rewrite Eq. (1) in the following form,

$$\delta L_n = 10 \log \left\{ \frac{\langle p_{nA}^2 \rangle}{\sum_n \langle p_{nA}^2 \rangle} \right\}, \quad (3)$$

where

$$\langle p_{nA}^2 \rangle = 10^{\delta L_n / 10} \langle p_n^2 \rangle. \quad (4)$$

Here $\langle p_n^2 \rangle$ and $\langle p_{nA}^2 \rangle$ express the average square sound pressure in the n -th frequency band and the A-weighted average square sound pressure in the same frequency band, respectively. Now it

becomes clear that the representative spectrum δL_n (Eq. 1) is related to the average square sound pressure, $\langle p_n^2 \rangle$. In the next section it will be shown that brackets $\langle \rangle$ mean the time average.

2. TIME-AVERAGE-MEAN-SQUARE SOUND PRESSURE

Assume that our task is to place a noise barrier close to a road. To use the appropriate noise spectrum, δL_n , we have to consider all vehicles which pass the receiver during time period T of the highest annoyance. Since the annoyance is measured by the time-average sound level, L_{AeqT} , the time period T under consideration corresponds to the maximum of L_{AeqT} (e.g. 8:00–9:00, rush hour traffic). Now, have a look at the definition of the time average sound level:

$$L_{AeqT} = 10 \log \left\{ \frac{\langle p_A^2 \rangle}{p_0^2} \right\}, \quad (5)$$

where

$$\langle p_A^2 \rangle = \frac{1}{T} \int_0^T p_A^2(t) dt \quad (6)$$

is the time-average-mean-square A-weighted sound pressure. It can be expressed as a sum of A-weighted average square sound pressures,

$$\langle p_{nA}^2 \rangle = \frac{10^{\delta L_n / 10}}{T} \int_0^T p_n^2(t) dt, \quad (7)$$

which have already appeared in the definition of δL_n (Eq. (3)).

To capture the intuition of a noise event, assume the noise is emitted by a stream of identical vehicles that pass the receiver with the same velocity, such that the time variation of $p_n^2(t)$ is as in Fig. 3. Because the pass-by time, τ , is much shorter than the averaging time T , we can write,

Fig. 3 Time variations of the square instantaneous sound pressure in the n -th frequency band for a stream of identical vehicles, which move with the same velocity.

$$\langle p_{nA}^2 \rangle = N \frac{10^{dL_n/10}}{T} E_n, \quad (8)$$

where N is the number of vehicles passing the receiver during the time T , and the integral

$$E_n = \int_{-\infty}^{\infty} p_n^2(t) dt \quad (9)$$

determines the sound exposure in the n -th frequency band. To be more realistic, suppose the noise has been produced by N real vehicles of the same category, either light or heavy. In such a case we obtain,

$$\langle p_{nA}^2 \rangle = N \frac{10^{dL_n/10}}{T} \bar{E}_n, \quad (10)$$

where $\bar{E}_n$ denotes the average over N vehicles, which have gone past the receiver during the time period T . Considering $E_n^{(1)}, E_n^{(2)}, \dots, E_n^{(N)}$ as a family of possible outcomes of the measurement, we apply the arithmetic average,

$$\bar{E}_n = \frac{1}{N} \sum_j E_n^{(j)}. \quad (11)$$

In reality the set of actual vehicles passing a given location differ from day to day. Thus we expect variations of N and $\bar{E}_n$.⁷⁾ To get the representative value of $\langle p_{nA}^2 \rangle$ and finally δL_n (Eq. (3)), we substitute the mean (over a few days) number of vehicles, $\bar{N}$, and the mean (over a few hundreds vehicles) sound exposure, $\bar{E}_n$, into Eq. (10).

For a stream of real vehicles that belong to two categories, the generalized form of Eq. (10) is,

$$\langle p_{nA}^2 \rangle = \bar{N} \frac{10^{dL_n/10}}{T} [(1-k) \cdot \bar{E}_{n1} + k \cdot \bar{E}_{n2}], \quad (12)$$

where $\bar{N}/T$ [veh/s] is the average flow rate of all vehicles (both light and heavy), and k is the average percentage of heavy vehicles. In the above expression $\bar{E}_{n1}$ and $\bar{E}_{n2}$ denote the mean sound exposure in the n -th frequency band for light and heavy vehicles, respectively. Substitution of Eq. (12) into Eq. (3) yields the representative normalized A-weighted sound pressure level (Eq. (1)),

$$\delta L_n = 10 \log \left\{ \frac{10^{dL_n/10} [(1-k) \cdot \bar{E}_{n1} + k \cdot \bar{E}_{n2}]}{\sum_n 10^{dL_n/10} [(1-k) \cdot \bar{E}_{n1} + k \cdot \bar{E}_{n2}]} \right\}. \quad (13)$$

Note, that the average flow rate, $\bar{N}/T$, has dropped out and the average percentage of heavy vehicles, k , remains as a single traffic characteristic during the most annoying time period T (e.g. 8:00–9:00 a.m.).

3. SOUND EXPOSURE

To calculate the sound exposure in the n -th frequency band, E_n (Eq. (9)), we have to know the time history of the square sound pressure in the corresponding frequency band, $p_n^2(t)$. In free space, a cruising vehicle can be modeled by a nondirectional point source, which produces the spherical wave,⁸⁾

$$p_n^2 = \frac{P_n \rho c}{4\pi r^2}. \quad (14)$$

Here P_n is the sound power in the n -th frequency band, ρc is the characteristic impedance of air, and r is the distance between source and receiver. Above the ground in the Earth's atmosphere, the calculation of $p_n^2(t)$ becomes more complex. The geometrical divergence given by Eq. (14) is disturbed by,

- ground effect,
- air absorption,
- scattering due to atmospheric turbulence,
- refraction caused by wind speed and temperature gradients.

Close to the source, the ground effect is the most important wave phenomenon,

$$p_n^2 = \frac{P_n \rho c}{4\pi r^2} \cdot G_n[d, H_s, H_o, \sigma], \quad (15)$$

where the ground factor $G_n^{9-11)}$ is a function of the horizontal distance d , and heights of the source, H_s , and the receiver, H_o (Fig. 4). Flow resistivity, σ , characterizes the ground covering. While a vehicle is moving, the time variations of both distances, $r(t)$ and $d(t)$, occur. Thus, Eq. (9) and Eq. (15) combine into,

$$E_n = \frac{P_n \rho c}{4s_0} \cdot J_n, \quad (16)$$

where $s_0 = 1 \text{ m}^2$ and the propagation factor, J_n , is given by an infinite integral,

$$J_n = \frac{s_0}{\pi} \int_{-\infty}^{\infty} \frac{G_n[d(t), H_s, H_o, \sigma]}{r^2(t)} dt. \quad (17)$$

Fig. 4 The direct and reflected ray paths going from the source, S, to the receiver, O.

Fig. 5 The vehicle *S* is moving with the speed *V* along the barrier at the perpendicular distance *D*.

Assuming the vehicle location and ground properties are strictly determined, the average sound exposure can be calculated from,

$$\overline{E_n} = \frac{\overline{P_n} \rho c}{4s_0} \cdot J_n, \quad (18)$$

where $\overline{P_n}$ means the average sound power in the *n*-th frequency band. For the purpose of noise barrier design, we consider vehicles which cruise with a steady speed, *V*, along the barrier at the perpendicular distance *D* (Fig. 5). Considering the height of the barrier as receiver's height, $H_o = H_B$, we get the explicit dependence of the distance, *r*, upon the time,

$$r = \{(Vt)^2 + D^2 + (H_s - H_o)^2\}^{1/2}. \quad (19)$$

Now, assuming that the height of a vehicle (H_s) is known, we are able to calculate the propagation factor, J_n , for any frequency band (Eqs. (17), (19)). Since the height of a light vehicle is different from that of a heavy vehicle, $H_{s1} \neq H_{s2}$, we can expect two different values of the propagation factor, J_{n1} and J_{n2} , for the same frequency band.

To obtain a first approximation to J_n , we set $H_{s1} = H_{s2} = 0$ for both categories of vehicles and

assume that the direct and reflected waves do not interfere with each other: $G_n = 2$. Thus, we arrive at the simplified form of the propagation factor (Eqs. (17), (19)),

$$J = \frac{2s_0}{V\sqrt{D^2 + H_o^2}}, \quad (20)$$

which is the same for each frequency band. Equalities, $J_1 = J_2 = \dots = J_n$, mean that the ground effect does not change the shape of the noise spectrum. However, for $H_s > 0$ it is no longer true.

4. SOUND POWER OF A VEHICLE

In this section we consider the average sound power, P_n , which is necessary for E_n (Eq. (18)) and ultimately for δL_n (Eq. (13)) calculation.

Yoshihisa *et al.*¹²⁾ have measured time average sound level, L_{ATn} , of traffic noise and then calculated the sound power, P_n , for different velocities *V*. Figure 6 shows an example of their results for light

Fig. 6 The sound power of noise, P_n , for the octave frequency band $f_n = 1,000$ Hz, which is generated by a light vehicle ($A_{n1} = 1.6 \cdot 10^{-8}$, $mn1 = 3.2$, see Table 1).

Table 1 Coefficients *A* and *m*, which determine the average sound power, $\overline{P_n}$, for light and heavy vehicles (Eqs. 21).

Frequency band f_n (Hz)	Light vehicles		Heavy vehicles	
	A_{n1}	$mn1$	A_{n2}	$mn2$
125	$3.31 \cdot 10^{-5}$	1.05	$5.93 \cdot 10^{-5}$	1.68
250	$1.48 \cdot 10^{-5}$	1.32	$1.47 \cdot 10^{-7}$	3.24
500	$4.13 \cdot 10^{-7}$	2.25	$2.71 \cdot 10^{-7}$	2.96
1,000	$1.64 \cdot 10^{-8}$	3.16	$1.65 \cdot 10^{-8}$	3.60
2,000	$4.08 \cdot 10^{-9}$	3.35	$7.40 \cdot 10^{-9}$	3.58
4,000	$1.28 \cdot 10^{-8}$	2.63	$2.32 \cdot 10^{-8}$	2.88

vehicles and $f_n = 1,000$ Hz. Regression analysis for 704 light vehicles yields,

$$\bar{P}_1 = 1.64 \cdot 10^{-8} \cdot (\bar{V})^{3.16},$$

where $\bar{V}$ expresses the average speed in km/h. For heavy vehicles and the same frequency band $f_n = 1,000$ Hz, we get

$$\bar{P}_2 = 1.65 \cdot 10^{-8} \cdot (\bar{V})^{3.60}.$$

So, for any frequency band (n) we can write,

$$\bar{P}_{n1} = A_{n1} \cdot \bar{V}^{mn1}, \quad \bar{P}_{n2} = A_{n2} \cdot \bar{V}^{mn2}. \quad (21)$$

Table 1 contains the complete set of coefficients A_{n1} , $mn1$ and A_{n2} , $mn2$, for both categories of vehicles. Equations (21) are used for the description of vehicle sound power in many countries.

5. NORMALIZED A-WEIGHTED SOUND PRESSURE SPECTRUM

In the most general case, when the ground effect modifies the noise spectrum and Eq. (17) yields different values of $J_{n1}(H_{S1}, \dots)$ and $J_{n2}(H_{S2}, \dots)$ for different frequency bands, the normalized A-weighted sound pressure spectrum can be calculated from (Eqs. (13), (18)),

$$\delta L_n = 10 \log \left\{ \frac{10^{4L_n/10} [(1-k) \cdot \bar{P}_{n1} \cdot J_{n1} + k \cdot \bar{P}_{n2} \cdot J_{n2}]}{\sum_n 10^{4L_n/10} [(1-k) \cdot \bar{P}_{n1} \cdot J_{n1} + k \cdot \bar{P}_{n2} \cdot J_{n2}]} \right\}. \quad (22)$$

Assuming $H_{S1} = H_{S2} = 0$ and a lack of coherence between the direct and reflected waves, Eq. (17) gives: $J_{n1} = J_{n2} = J$ (Eq. 20). In such a case, expression (22) simplifies to the form,

$$\delta L_n = 10 \log \left\{ \frac{10^{4L_n/10} [(1-k) \cdot \bar{P}_{n1} + k \cdot \bar{P}_{n2}]}{\sum_n 10^{4L_n/10} [(1-k) \cdot \bar{P}_{n1} + k \cdot \bar{P}_{n2}]} \right\}. \quad (23)$$

Finally, when a stream of vehicles is moving with a steady speed, V , by substitution of Eqs. (21) into Eq. (23) we obtain,

$$\delta L_n = 10 \log \left\{ \frac{10^{4L_n/10} [(1-k) \cdot A_{n1} \cdot \bar{V}^{mn1} + k \cdot A_{n2} \cdot \bar{V}^{mn2}]}{\sum_n 10^{4L_n/10} [(1-k) \cdot A_{n1} \cdot \bar{V}^{mn1} + k \cdot A_{n2} \cdot \bar{V}^{mn2}]} \right\}, \quad (24)$$

where coefficients A and m (for Japanese roads) are given in the Table 1.

In a particular case of road traffic, which consists only from light vehicles, $k=0$, Eq. (24) takes the

form,

$$\delta L_n = 10 \log \left\{ \frac{10^{4L_n/10} \cdot A_{n1} \cdot \bar{V}^{mn1}}{\sum_n 10^{4L_n/10} \cdot A_{n1} \cdot \bar{V}^{mn1}} \right\}. \quad (25)$$

In all above equations, the traffic velocity, $\bar{V}$, is expressed in kilometers per hour.

6. NOISE SPECTRA OF TRAFFIC FROM JAPANESE ROADS

Let's assume that vehicles of both categories are moving with the same speed, V . Figure 7 shows

Fig. 7 The normalized A-weighted sound pressure spectrum (Eqs. (1), (24)) for traffic speed $V=60$ km/h and $k=0$ (—), 0.05 (---), 0.2 (····), 0.6 (-·-·-), and 1.0 (— · — · —).

Fig. 8 The normalized A-weighted sound pressure spectrum (Eqs. (1), (24)) for traffic speed $V=100$ km/h and $k=0$ (—), 0.05 (---), 0.2 (····), 0.6 (-·-·-), and 1.0 (— · — · —).

the changes of the normalized A-weighted sound pressure spectrum, δL_n (Eq. (24)), when the percentage of heavy vehicles increases from $k=0$ to $k=1$, while $V=60$ km/h. The values of δL_n for low frequencies ($f < 500$ Hz) increase with increasing k . In Fig. 8 the variations of δL_n with k are presented, while the speed $V=100$ km/h. In the latter case the influence of heavy vehicles on δL_n is more distinct.

7. CONCLUSIONS

Equation (24) makes it possible to calculate the representative spectrum of traffic noise, *i.e.*, the normalized A-weighted sound pressure level, δL_n (Eq. (1)), when the average traffic speed $\bar{V}$ (km/h) and the percentage of heavy vehicles, $0 \leq k \leq 1$, are known. Our results indicate that both quantities, *i.e.* $\bar{V}$ and k , play an important role, especially at frequencies less than 500 Hz (Figs. 7, 8).

Inspection of Fig. 1 and Fig. 8 leads to the conclusion that the representative spectrum of noise traffic for European roads is almost identical with that for Japanese roads, when the traffic speed equals $V=60$ km/h and the percentage of heavy vehicles is $k=0.2$.

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