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ROAD TRAFFIC NOISE FROM A STOPPING LINE

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A simple method, requiring simultaneous noise measurements at three positions is presented for the prediction of the equivalent continuous sound level, L_{AeqT}, of road traffic noise generated at the stopping line. Geometrical spreading of noise is affected by reflection from the hard ground surface. This method can be applied when noise is produced by vehicles of one category, the traffic streams in both directions are almost identical, and the perpendicular distance between the road axis and the receiver exceeds the road width.

1. Introduction

Noise due to the stop-and-go motion of road vehicle has been extensively studied [1, 3, 5-18]. The most complete summary of the previous results can be found in Bowlby *et al.* [1]. To simplify the theory, i.e., to decrease the number of variables involved, we consider the following case:

- The number of medium sized and heavy vehicles is negligible, so there is only one category of noise sources, i.e., cars;
- Cars move in both directions along a road with one stopping line;
- There are two modes of motion: cruising with steady speed and stopping;
- Noise is quantified by the equivalent continuous sound level, L_{AeqT}.

The above assumptions lead to the equation,

$$L_{AeqT} = 10\lg\left\{\frac{\langle p_{A1}^2\rangle + \langle p_{A1}^2\rangle}{p_o^2}\right\}, \quad p_o = 20\ \mu\text{Pa}, \tag{1}$$

where

$$\langle p_{A1}^2\rangle = \frac{1}{T}\int_0^T p_{A1}^2(t)\,dt, \qquad \langle p_{A2}^2\rangle = \frac{1}{T}\int_0^T p_{A2}^2(t)\,dt, \tag{2}$$

are the time-average A-weighted squared sound pressures due to cruising and stopping vehicles, respectively.

Discussion of road traffic (Sec. 2) is followed by a discussion of noise propagation (Sec. 3). The theory contains three adjustable parameters that can be estimated at the site of interest (Sec. 4).

2. Road traffic

Because the distance between the receiver and the road axis exceeds the road width, we do not distinguish between traffic lanes. During a time interval T, N_1 vehicles cruise without stopping and N_2 vehicles are stopped. Traffic is interrupted many times and the queues are formed on the left and right side of the stopping line. During the time interval T, the total number of stopping vehicles on both sides of the stopping line is nearly the same, $N_2/2$, and the average lengths of corresponding queues, L, are equal to each other (Fig. 1). We now introduce the distance between the stopping line, $x = 0$, and the k-th vehicle in the queue: $\pm x_k$, where $k = 1, 2, 3, \ldots$ If the distance between the two consecutive vehicles is ΔL, then $x_k = k \cdot \Delta L$. Let $n(+1)$ and $n(-1)$ be the total number of vehicles waiting during the time interval T at the nearest distances: $+x_1 = +1 \cdot \Delta L$, and $-x_1 = -1 \cdot \Delta L$. For the distances, $+x_2 = +2 \cdot \Delta L$ and $-x_2 = -2 \cdot \Delta L$, i.e. for each vehicle waiting as a second in the queue (on both sides of the stopping line), we write $n(+2)$ and $n(-2)$, respectively. In general, $n(k)$ expresses the number of vehicles waiting at the distances, $\pm x_k = \pm k \cdot \Delta L$, where

$$\sum_{k=1}^{+\infty} n(k) = N_2/2. \tag{3}$$

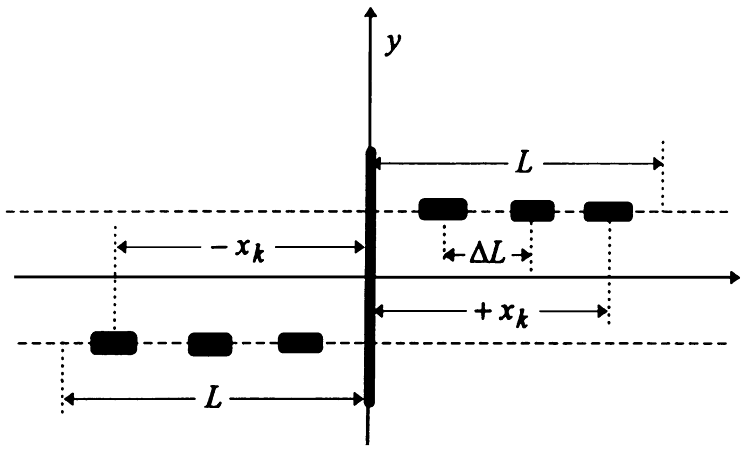

Fig. 1. Queues of waiting vehicles with the average length, L, the same on both sides of the stopping line.

Due to the similarity of traffic streams in both directions, we expect the distribution of $n(k)$ as is shown in Fig. 2. For a one parameter distribution, the number of vehicles

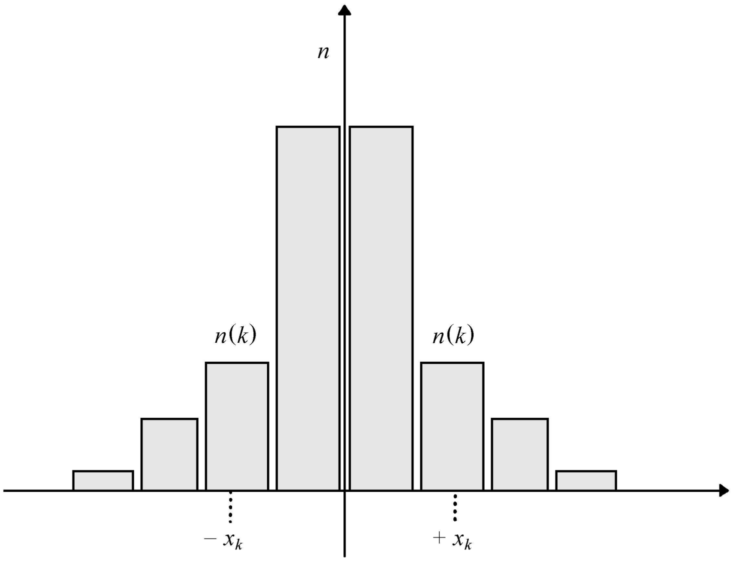

Fig. 2. Space distribution of vehicles in the queue, where $n(k)$ denotes the number of vehicles stopping during the time interval, T, at distance, $+x_k$ and, $-x_k$.

stopping at distance, x_k, is

$$n(k) = \frac{N_2}{2} f(k, \lambda), \tag{4}$$

where the frequency function meets the condition,

$$\sum_{k=1}^{+\infty} f(k, \lambda) = 1. \tag{5}$$

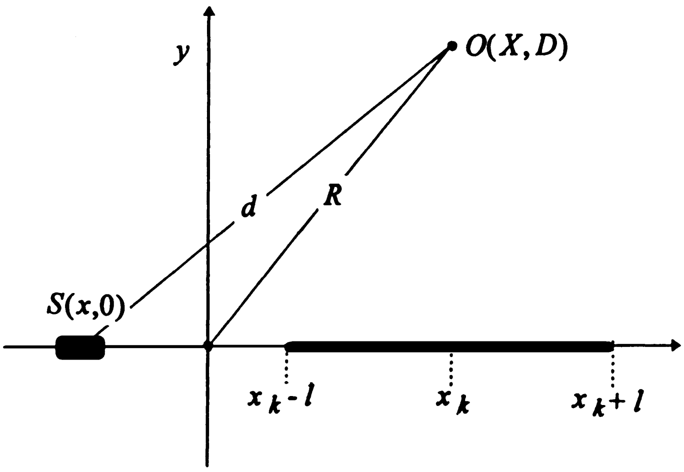

Fig. 3. Distance d between the receiver O and the vehicle S (Eq. (8)) and the distance R between the receiver and the center of the stopping line (Eq. (35)).

For example, using the exponential function we obtain,

$$f = \left(e^{\lambda} - 1\right) e^{-\lambda k}. \tag{6}$$

Figure 10.3 in FAVRE [6] indicates that within a town the deceleration and acceleration lengths are approximately equal to each other, $l_1 \approx l_2 \approx l$. Thus, the k-th vehicle in the queue moves with a steady speed, $V = V_o$, along two road segments $(-\infty, x_k - l)$ and $(x_k + l, +\infty)$, whereas on the road segment $(x_k - l,\ x_k + l)$ its speed is varying, $V = V(x)$ (Fig. 3).

3. Noise propagation

In a free space, within 100 m from the source, noise propagation is governed mainly by geometrical spreading and ground effect [4]. When the ground surface is hard and plain, the only result of ground reflection is the virtual change of the sound power. Thus, the A-weighted squared sound pressure of noise produced by a road vehicle is,

$$p_A^2 = \frac{\widetilde{W}_A \rho c}{4\pi d^2}, \tag{7}$$

where $\widetilde{W}_A = \beta W_A$ is the virtual A-weighted sound power and ρc is the characteristic impedance of air. Introducing the coordinates of the receiver (X, D) and coordinates of the moving vehicle $(x, 0)$, the instanteneous distance between them equals (Fig. 3),

$$d \approx \sqrt{(x - X)^2 + D^2}. \tag{8}$$

The above approximation holds when the road width is less than the perpendicular distance to the receiver, D. For the varying speed (either acceleration or deceleration), the sound exposure is,

$$E = \int\limits_{-\infty}^{+\infty} \frac{p_A^2(x)}{V(x)}\, dx. \tag{9}$$

The varying velocity, $V(x)$, is accompanied by varying sound power, $\widetilde{W}_A(x)$, so Eqs. (7)–(9) yield,

$$E = \frac{\rho c}{4\pi} \int\limits_{-\infty}^{+\infty} \frac{S(x)}{d^2(x)}\, dx, \tag{10}$$

where

$$S(x) = \frac{W_A(x)}{V(x)}, \tag{11}$$

defines the A-weighted sound energy density expressed in Joules per meter. The road appears to be a line source. For a vehicle cruising non-stop $(-\infty, +\infty)$ with the speed $V = V_o$, the sound exposure becomes,

$$E_1 = \frac{\rho c}{4D} S_1, \tag{12}$$

where the cruise sound energy density is, $S_1 = W_A(V_o)/V_o$. Thus, noise generated by N_1 cruising vehicles, during the time interval T, can be quantified by (Eqs. (2), (12)),

$$\langle p_{A1}^2 \rangle = \frac{N_1}{T} E_1. \tag{13}$$

We now describe noise generated during the time interval T by N_2 stopping vehicles. Because the average number of vehicles halting at both sides of the stopping line is nearly the same, $n(+k) \approx n(-k)$, we write (Eq. (2)),

$$\langle p_{A1}^2 \rangle = \frac{1}{T} \sum_{k=1}^{+\infty} n(k) \cdot [E(+k) + E(-k)], \tag{14}$$

where $E(+k)$ and $E(-k)$ denote the sound exposure for the vehicle waiting at the distances, $+x_k$, and $-x_k$, respectively. To find $E(+k)$ and $E(-k)$, first from Eq. (10) we calculate noise from cruise segments, $(-\infty,\, x_k - l)$ and $(x_k + l,\, +\infty)$ (Fig. 3),

$$E_c(k) = E_1 \cdot [1 - F(x_k)], \tag{15}$$

where

$$F(x_k) = \frac{1}{\pi} \left[\tan^{-1} \frac{x_k + l - X}{D} - \tan^{-1} \frac{x_k - l - X}{D} \right]. \tag{16}$$

Noise emitted during deceleration and acceleration is described by the sound exposure (Eq. (10)),

$$E_s(k) = \frac{\rho c}{4\pi} \int_{x_k - l}^{x_k + l} \frac{S(x)}{d^2(x)}\, dx. \tag{17}$$

The mean value theory of integral calculus yields [2],

$$E_s(k) = \frac{\rho c}{4D} S(x_*) F(x_k), \tag{18}$$

where $S(x_*)$ expresses the average value of the A-weighted sound energy density from the road segment, $(x_k - l,\, x_k + l)$ and $F(x_k)$ is defined by Eq. (16).

When $S(x_*)$ exceeds m times the A-weighted cruise sound energy, $S(x_*) = m \cdot S_1$, the sound exposure for the stopping vehicle is, $E = E_s + E_c$ (Eqs. (12), (15), (18)),

$$E(\pm k) = E_1 \cdot [1 + (m-1) F(\pm x_k)]. \tag{19}$$

Combining Eqs. (1), (3), (4), (13), (14), (19) yields the equivalent continuous sound level for noise emitted by all cruising and stopping vehicles,

$$L_{AeqT} = L_{AeqT}(D) + \Delta L_{AeqT}(X, D), \tag{20}$$

where

$$L_{AeqT}(D) = L_s + 10 \lg \left\{ \frac{(N_1 + N_2) d_o t_o}{4DT} \right\}, \quad d_o = 1 \text{ m}, \quad t_o = 1 \text{ s}, \tag{21}$$

quantifies road traffic noise far away from the stopping line, $|X| > l + L$ (Figs. 1, 3). Here L_s denotes the level of sound energy density (Eq. (12)),

$$L_s = 10 \lg \left\{ \frac{S_1 d_o}{W_o t_o} \right\}, \quad W_o = 10^{-12} \text{ Watts}. \tag{22}$$

In Eq. (20) the noise contribution from stopping vehicles is quantified by,

$$\Delta L_{AeqT} = 10\lg\left\{1 + \frac{N_2}{N_1+N_2}(m-1)\cdot M(X,D,\lambda)\right\}, \tag{23}$$

where function $M(X,D,\lambda)$ accounts for the space distribution of waiting vehicles (Eq. (16)),

$$M = \frac{1}{2}\sum_{k=1}^{+\infty} f(k,\lambda)\left[F(+x_k,X,D) + F(-x_k,X,D)\right]. \tag{24}$$

4. Parameter estimation

The above equations show that the theory incorporates three adjustable parameters, i.e., L_s, m, and λ. To determine L_s and m, two microphones must be located far away from the queue. For a value of coordinate X much greater than the maximum of x_k (queue length), function M (Eq. (24)) simplifies to the form,

$$M(X,D) \approx \frac{1}{\pi}\left[\tan^{-1}\frac{X+l}{D} - \tan^{-1}\frac{X-l}{D}\right], \tag{25}$$

and the equivalent continuous sound level is given by (Eqs. (20), (21), (23), (25)),

$$L_{AeqT}(X) = L_s + 10\log\left\{\frac{d_o t_o}{4DT}\left[N_1 + N_2\cdot(1+(m-1)M(X,D))\right]\right\}. \tag{26}$$

If two simultaneous measurements, $L_{AeqT}(X_1)$, and $L_{AeqT}(X_2)$, are performed at the same perpendicular distance, D_o (Fig. 4), then Eq. (26) yields

$$m = \frac{N_1+N_2}{N_2}\,\frac{q-1}{M(X_1,D_o) - k\cdot M(X_2,D_o)} + 1, \tag{27}$$

where

$$q_1 = 10^{[L_{AeqT}(X_1) - L_{AeqT}(X_2)]/10}. \tag{28}$$

By substituting the parameter m into Eq. (26), the level of the sound energy density L_s is obtained.

To determine adjustable parameter λ, we place the microphone in front of the stopping line, $X = 0$, and at the perpendicular distance D_o much less than the acceleration length l. In such a case function M (Eq. 24) can be approximated by,

$$M(\lambda) \approx 1 - \frac{2D_o}{\pi l}\left[1 + \frac{1}{l^2}\sum_{k=1}^{+\infty} f(k,\lambda)\cdot x_k^2\right]. \tag{29}$$

The equivalent continuous sound level is (Eqs. (20), (21), (23), (29)),

$$L_{AeqT}(0) = L_s + 10\log\left\{\frac{d_o t_o}{4DT}\left[N_1 + N_2\cdot(1+(m-1)M(\lambda))\right]\right\}. \tag{30}$$

When $L_{AeqT}(0)$ is measured and both parameters, L_s and m, are already known, the above equation can be used for the estimation of λ. To find its value, however, the explicit form of $M(\lambda)$ must be known. For example, with the distribution of vehicles in the queue defined by Eq. (6) and the distance to the k-th vehicle, $x_k = k \cdot \Delta L$ (Fig. 1), we arrive at (Eq. (29)),

$$M(\lambda) \approx 1 - \frac{2D_o}{\pi l}\left[1 + \left(\frac{\Delta L}{l}\right)^2 \frac{1+e^{-\lambda}}{(1-e^{-\lambda})^2}\right]. \tag{31}$$

5. Example

The measurements of the 10-minutes ($T = 600$ s) equivalent continuous sound level, L_{AeqT}, were performed at the longitudinal distances, $X_1 = 40$ m, and $X_2 = 60$ m, from the stopping line (in any other case these distances can be different). Both microphones were located at the height 1 m with the perpendicular distance, $D_o = 8$ m, from the road axis (Fig. 4). During 8 Fridays, between 2 p.m. and 4 p.m., we performed 32 measurements of $L_{AeqT}(40)$ and $L_{AeqT}(60)$. Each time, the total number of cruising vehicles (N_1) and stopping vehicles (N_2) were counted. The acceleration length was approximately equal to the deceleration length, $l \approx 25$ m, and the distance between the consecutive vehicles in the queue was, $\Delta L \approx 7$ m. The average results of the measurements are: $L_{AeqT}(40) = 71.5$ dB, $L_{AeqT}(60) = 71.1$ dB, and the number of cruising and stopping vehicles were, $N_1 = 118$, $N_2 = 563$, respectively.

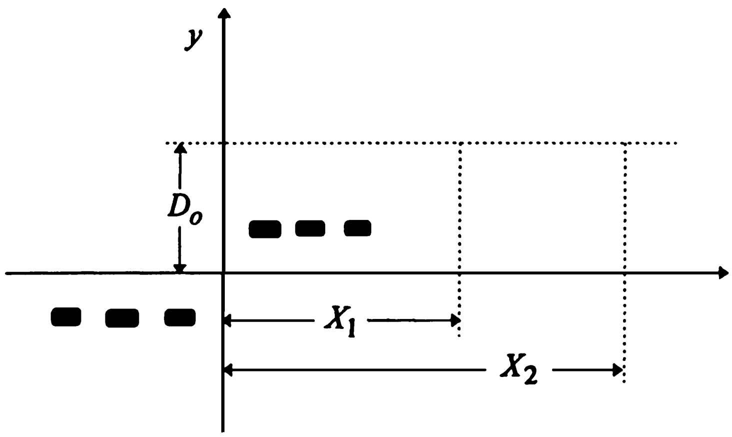

Fig. 4. Microphone location during the simultaneous measurement of the equivalent continuous sound levels, $L_{AeqT}(X_1)$ and $L_{AeqT}(X_2)$.

Making use of Eqs. (26) and (27) we get the adjustable parameters, $m = 4.96$, and $L_s = 88.3$ dB. To estimate the remaining parameter, λ, simultaneous measurements of $L_{AeqT}(0)$ were done, opposite to the stopping line, $X = 0$, with the perpendicular distance, $D_o = 8$ m. The average $L_{AeqT}(0) = 72.9$ dB, with $m = 4.94$ and $L_s = 88.3$ dB, yields (Eqs. (30), (31)): $\lambda = 0.34$.

6. Discussion

When the adjustable parameters, L_s, m, and λ, are available, one is able to calculate the value of M (Eq. 24) for any longitudinal distance, $-\infty < X < +\infty$, and the perpendicular distance, D, greater than the road width,

$$M = \frac{e^{\lambda} - 1}{2\pi} \sum_{k=1}^{+\infty} e^{-k\lambda} \Phi(X, D, k), \tag{32}$$

with the angle,

$$\Phi = \tan^{-1} \frac{X + l - k\Delta l}{D} - \tan^{-1} \frac{X - l - k\Delta l}{D} + \tan^{-1} \frac{X + l + k\Delta l}{D} - \tan^{-1} \frac{X - l + k\Delta l}{D}. \tag{33}$$

When the perpendicular distance, D, exceeds the acceleration length, l, then the value of M can be calculated from,

$$M \approx \frac{2lD}{\pi R^2} \left(1 + \frac{l^2 - q^2}{R^2}\right), \tag{34}$$

where

$$R = \sqrt{X^2 + D^2} \tag{35}$$

is the distance between the receiver and the center of the stopping line (Fig. 3), and

$$q^2 = \frac{1 + e^{-\lambda}}{(1 - e^{-\lambda})^2} (\Delta L)^2. \tag{36}$$

In such a case, the equivalent continuous sound level is (Eq. 20),

$$L_{AeqT} = L_{AeqT}(D) + \Delta L_{AeqT}(R), \tag{37}$$

where $L_{AeqT}(D)$ (Eq. (21)) gives the noise level far away from the stopping line, $|X| > l + L$, and

$$\Delta L_{AeqT}(R) = 10 \lg \left\{1 + \frac{N_2}{N_1 + N_2} \frac{ld_o}{\pi R^2} (m - 1) \left(1 + \frac{l^2 - q^2}{R^2}\right)\right\}, \tag{38}$$

accounts for noise from stopping vehicles.

7. Conclusions

When the assumptions cited in the Introduction are fulfilled and the space distribution of vehicles in the queue is described by Eqs. (3)-(5), the equivalent continuous sound level, L_{AeqT}, at any location (X, D), can be calculated from Eq. (20). To do that, the numerical values of adjustable parameters, L_s, m, and λ, have to be found from three simultaneous measurements of L_{AeqT}. In this study we considered the influence of stopping line on noise produced by cars, $\Delta L^{(1)}_{AeqT}$ (Eqs. (23), (38)). For the truck noise one can write, $\Delta L^{(2)}_{AeqT}$. Some measurements indicate that the influence of stopping line on truck noise is greater than for car noise: $\Delta L^{(2)}_{AeqT} > \Delta L^{(1)}_{AeqT}$. In the near future this problem will be under consideration.

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