New Mathematical Model to Estimate Road Traffic Noise in View of the Appearance Rate of Heavy Vehicles

Mitsunobu Maruyama
Acoustical Science Laboratory, 6-5-5-105, Josuihon-cho, Kodaira City, 187-0022 Japan

Kazuhiro Kuno
Department of Electrical Engineering, Aichi Institute of Technology, 1247 Yachigusa, Yakusa-cho, Toyota City, 470-0392 Japan

Toshio Sone
Tohoku University, 4-9-5 Midorigaoka, Taihaku-ku, Sendai City, 982-0021 Japan

A new mathematical model is proposed to estimate road traffic noise at sites along a freeway where the traffic volume fluctuates from a maximum of 900 vehicles per hour in the daytime to a minimum of 300 vehicles per hour at night. The model considers traffic conditions such as the percentage of heavy vehicles, time interval between successive (two or more) heavy vehicles and measurement time interval. The A-weighted equivalent continuous sound pressure levels calculated from this model are in keeping with measured ones at several representative time intervals both in the daytime and nighttime.

1. INTRODUCTION

Road traffic noise is a type of random variable noise, and its magnitude is widely scattered according to traffic conditions such as traffic volume, traffic content, vehicle speed, and meteorological conditions. These conditions include the direction and velocity of the wind, temperature, humidity, and atmospheric pressure, as well as the distance and nature of the ground surface from the road to an observation point.[1–5] Although a mathematical model should consider as many of the aforementioned factors as possible, most models consider only a few factors due to estimation complexity.

Today when new roads are being planned, an environmental assessment concerning road traffic noise and vibration should be conducted. Accordingly, a model to predict road traffic noise (RTN) is essential. Although predicted estimates such as $L_{Aeq,T}$ and $L_{AN,T}$ must meet the environmental standards set up in each country, the accuracy of the prediction affects the assessment results.[6–9] Hence, many prediction models have been developed along with methods to calculate the RTN in each country.

For example, the CoRTN model was developed by M. E. Delany et al. of the Department of Environment in the United Kingdom. In this model the hourly value of L_{10} with corrections for mean speed, percentage of heavy vehicles, gradient, and feature of road surface is calculated first.[10,11] RLS 90 is the standard for noise prediction in Germany. The mean A-weighted sound pressure level is calculated as a function of emission level, attenuation due to ground and atmospheric effects, and the attenuation due to the topography and building dimensions.[12] On the other hand, the USA used to employ the FHWA Traffic Noise Prediction Model developed by Barry and Reagan of the Department of Transportation Federal Highway Administration.[13] This model has been published as Report No FHWA-RD-77-108 and includes a calculator program. However, the program has been developed successively under the title of STAMINA.[14] In this model, $L_{Aeq,1\mathrm{h}}$ is estimated on the basis of the A-weighted average sound pressure level at the reference distance (usually 15 m). Version 3.0 is widespread at the moment.[15] The Acoustical Society of Japan published the first version of a method to predict RTN in 1975, which has been revised about every five years. The most recent version is the ASJ RTN-Model 2008, which was published in 2010.[16] The ASJ-Model adopts a method to obtain $L_{Aeq,T}$ based on a single event sound exposure level, L_{AE}.

The measured value of $L_{Aeq,T}$ depends not only on the nature of noise fluctuation but also on the measurement time interval T. However, the measurement time interval is not clearly specified in ISO 1996 and JIS Z 8731, and, thus, can be arbitrarily chosen (e.g., 1 hour, 24 hours, or a week). ISO 1996-Part 2 states that the measurement time intervals shall be such that all significant variations in noise emissions and transmissions are covered.[17–19]

This study has two main goals:

a) To propose a model that simply predicts RTN even at a road or for a time interval with light traffic.

b) To determine an appropriate method to select the measurement time interval T for obtaining a valid and accurate $L_{Aeq,T}$.

Previous models to predict $L_{Aeq,T}$ at a site along a highway assume that traffic volume, vehicle speed, percentage of heavy vehicles, and accompanying conditions are stable during the measurement time interval T. Thus, they are static models in which $L_{Aeq,T}$ [dB] is uniquely determined according to the given conditions. However, people dwelling in the area along roads having less traffic than 1,000 vehicles per hour are often annoyed by the passing of heavy vehicles, especially at nighttime, even though the daily L_{Aeq} or nighttime L_{Aeq}

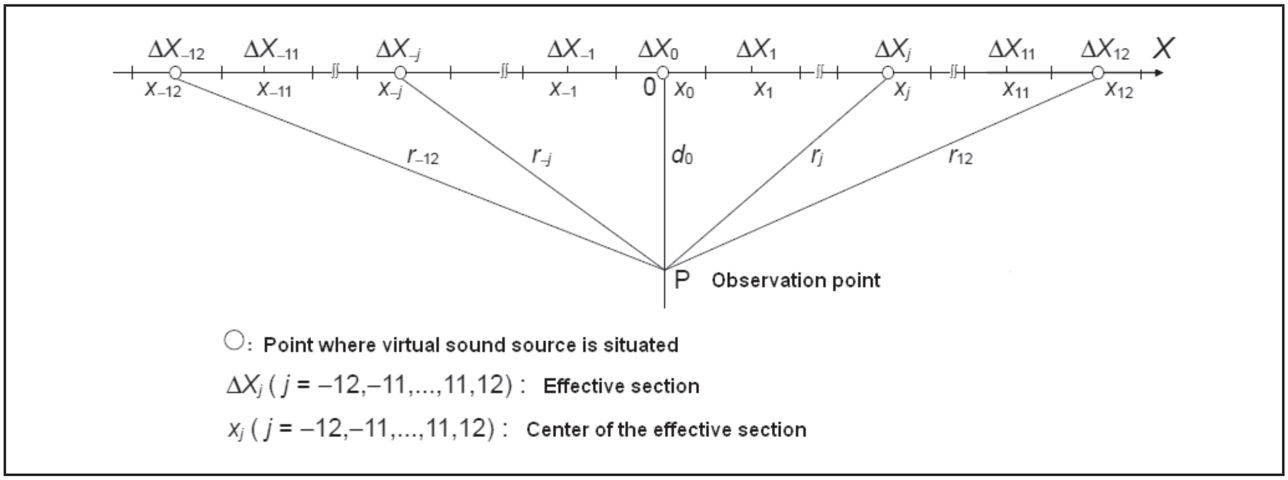

Figure 1. Configuration of the effective sections on the road.

is quite low. Our model is intended eventually to obtain the evaluation method for annoyance in such a situation by simulating the temporal variation in road traffic noise, preferably in the way consistent with the existing models. Although the dynamic property of RTN comes into view in our study, the results of prediction are compared for the same traffic conditions as those obtained from two typical static models, FHWA model and ASJ RTN-Model 1993.[14,20] This report is the first in a series of such studies.

Our model assumes that every automobile runs freely at steady speed on a flat and straight road one by one. For verification, $L_{Aeq,1h}$'s were measured every hour throughout a 24-hour period. As shown later, the measured data agrees well with estimated ones.

2. MATHEMATICAL MODEL TO REPRESENT THE SOUND INTENSITY OF TIME-VARYING NOISE

2.1. Model of Traffic Flow that Divides the Road into Small Sections along its Length

If the distance between two successive cars running at a steady speed on a freeway is assumed to obey the exponential distribution, and if road traffic is simulated using random numbers exponentially distributed, then the inconvenience that the interval between two successive cars is zero or excessively short often occurs. Hence, herein an exponential distribution where such an inconvenience is avoidable is considered.

Our model assumes that the road is flat, straight, and covered by a reflective material. The center line of the road is taken as the x-axis, and the foot of a perpendicular drawn from observation point P to it is taken as its origin O. The length of line OP is indicated by d_0 [m], and the right side of O is the positive direction (Fig. 1). The assumption is that all the cars are running at steady speed of $\overline{v}$ [m/h] along the x-axis from left to right while maintaining a safe interval between the two cars. Consequently, one car cannot overtake another. Generally, the distance between the two successive cars required for safe driving on a freeway is roughly $\overline{v} \times 10^{-3}$ m or more.[21] Hereafter this minimum allowable distance between the two successive cars is represented by D_{min} m. Namely, if a car runs at an average speed of $\overline{V}$ = 80, 100, or 120 km/h, then D_{min} is 80, 100, or 120 m, respectively. Thus, there is a relation of $\overline{v} = 1000\overline{V}$. If the traffic volume per hour is shown as Q [vehicles/h], the probability density function of distance D is given by:

$$P(D) = \lambda_D \exp(-\lambda_D(D - D_{min})), \tag{1}$$

where the average distance between successive two cars, $\overline{D} = 1/\lambda_D + D_{min}$, obeys an exponential distribution and $\lambda_D = Q/(\overline{v} - Q \cdot D_{min})$. In addition, it is assumed that (a) a car is a point source noise emitter; (b) there is not another noise source nearby; (c) the sound propagation path from the source to the observation point is free of obstacles; and (d) the sound level does not fluctuate due to meteorological origins.

Dividing the center line of the road into consecutive sections with the same length ΔX_j ($j = \pm 1, \pm 2, \pm 3, \ldots$) where ΔX_0 is the center, the center of each section is placed at $x_1, x_2, x_3, \ldots$ along the x-axis in the positive (right) direction and $x_{-1}, x_{-2}, x_{-3}, \ldots$ in the negative (left) direction. If the length of the j-th section, ΔX_j, is appropriately selected relative to d_0, then the total level of sound from the vehicles within a section can be replaced by that from a single source with sound power W_j [W] placed at the center of the section, x_j, where W_j is the sum of the sound power emitted from all vehicles present in section ΔX_j.

2.2. Relation Between the Length of a Section, ΔX_j, and d_0

Suppose a vehicle with sound power W is located at the center x_j of the j-th section, ΔX_j, and another vehicle emitting sound at the same power is located at either end ($x_j \pm \Delta X_j/2$) of the section. Then the difference in the level at point P between the sounds from both vehicles is expressed as:

$$\Delta L_j = 10 \log_{10} \left[\frac{\frac{W}{2\pi(d_0^2 + x_j^2)}}{\frac{W}{2\pi\{d_0^2 + (x_j \pm \Delta X_j/2)^2\}}} \right] \quad \text{[dB]}. \tag{2}$$

If

$$|\Delta L_j| \leq 1 \quad \text{[dB]}, \tag{3}$$

then both sound sources have equivalent in sound emissions. ΔX_j that satisfies both Eqs. (2) and (3) can be obtained. Substituting Eq. (2) into Eq. (3) yields:

$$x_j^2 \pm 4\Delta X_j x_j + (d_0^2 - \Delta X_j^2) \geq 0. \tag{4}$$

Discriminant D may be required to satisfy Eq. (4) to be valid:

$$D = 4\Delta X_j^2 - (d_0^2 - \Delta X_j^2) \leq 0. \tag{5}$$

Thus, ΔX_j is bounded by:

$$0 \leq \Delta X_j \leq \frac{d_0}{\sqrt{5}} \left(\cong \frac{d_0}{2} \right). \tag{6}$$

For an arbitrary j-th section, if ΔX_j is nearly equal to $d_0/2$, the replacement mentioned in the last part of Section 2.1 is valid.

2.3. Extent of Effective Sections

In principle, the intensity of sound arriving at point P is the superposition of sounds from an infinite number of virtual point sources placed at each x_j ($-\infty < j < +\infty$), although the effective sources actually exist in ΔX_0 and sections close to it. In other words, it is sufficient to consider a limited number of sections with ΔX_0 as the center. Hereafter, the number of such sections is called the number of effective sections.

Let us consider the number of effective sections. Assuming that the average sound power of a single vehicle, including n_p passenger cars each with a sound power W_p and n_t heavy vehicles each with a sound power W_t, is $\overline{W}$ within ΔX, then:

$$\overline{W} = \frac{W_p \overline{n_p} + W_t \overline{n_t}}{\overline{n_p} + \overline{n_t}} \quad \text{[W]}. \tag{7}$$

The intensity of sound at P is obtained as the sum of those coming from virtual sources placed at each center of the sections. Thus, the intensity of sound at P is denoted by:

$$I_{\pm\infty} = \sum_{j=0}^{\pm\infty} \frac{\overline{nW}}{2\pi} \cdot \frac{1}{d_0^2 + (j\Delta X_0)^2} \quad \text{[W/m}^2\text{]}, \tag{8}$$

where $n = n_p + n_t$.

If the number of effective sections is $2J + 1$, then the intensity of sound originating from all the vehicles within sections from $j = 0$ to $\pm J$ at observation point P can be written as:

$$I_{\pm J} = \sum_{j=0}^{\pm J} \frac{\overline{nW}}{2\pi} \cdot \frac{1}{d_0^2 + (j\Delta X_0)^2} \quad \text{[W/m}^2\text{]}. \tag{9}$$

If the following equation is satisfied, then $2J + 1$ can be regarded as the number of effective sections:

$$10 \log_{10} \left(\frac{I_{\pm J}}{I_{\pm\infty} - I_{\pm J}} \right) \geq 10 \quad \text{[dB]}, \tag{10}$$

where the subscript I must be this order of compound. Substituting Eq. (8) and Eq. (9) for Eq. (10) gives:

$$J = 12. \tag{11}$$

Hence, the number of effective sections is 25.

2.4. Sound Intensity and a Suitable Integration Time

In this estimation method the intensity of sound arriving at the observation point from each virtual sound source varies stepwise with time. The relation between the intensity of sound arriving at observation point P at time t and the integration time for the sound energy to be observed is considered here.

Sound arriving at P at time t from a virtual source passing by the reference point $x_0 (= 0)$ should be emitted from the source at time $t - d_0/c$ where c is the sound velocity. As shown in Fig. 1, the power of a sound emitted from each virtual source is assumed to be $W_{-12}, \ldots, W_{-j}, \ldots, W_0, \ldots, W_j, \ldots, W_{12}$ at time $t - d_0/c$. Because the sound power of a source in the ΔX_j section varies stepwise with time, the change is approximated by the source passing on along a lane from left to right instantaneously every $\Delta X/v$ [s]. The sound power W_j of a source placed at x_j at time $t - d_0/c$ remains constant until $t - d_0/c + d_0/2v$, and then the sound power of a source at x_j changes to W_{j-1} and is kept constant during $d_0/2v$, and so forth.

According to this approximation, if the average integration time for sound energy at P is $d_0/2v$, then it can be assumed that the macroscopic property of sound intensity fluctuation is maintained even though information of the stepwise variation of sound power from each virtual source is lost. Here, v [m/s] is the average car speed per second, and has the relation of $v = \overline{v}/3600$ with $\overline{v}$ [m/h]. Table 1 shows the time when sound is radiated from each virtual source as well as the sound energy to be integrated at observation point P during time t to $t + d_0/2v$. Representing this energy as $J_P(t; d_0/2v)$, it is expressed as:

$$J_P(t; d_0/2v) = \sum_{j=-12}^{12} \frac{J_j(t; d_0/2v)}{2\pi r_j^2}, \tag{12}$$

where $r_j^2 = d_0^2 + \left(\frac{jd_0}{2}\right)^2 = d_0^2 \left(1 + \frac{j^2}{4}\right)$, and

$$J_j(t; d_0/2v) = n_{j+1} W_{j+1} \left(\frac{d_0}{c}\right) \left\{ \sqrt{1 + \left(\frac{j}{2}\right)^2} - 1 \right\} + n_j W_j \left\{ \frac{d_0}{2v} - \frac{d_0}{c} \left(\sqrt{1 + \left(\frac{j}{2}\right)^2} - 1 \right) \right\}. \tag{13}$$

This equation can be transformed into:

$$J_j(t; d_0/2v) = n_j W_j \left(\frac{d_0}{2v}\right) + \left(\frac{d_0}{c}\right) \left\{ \sqrt{1 + \left(\frac{j}{2}\right)^2} - 1 \right\} (n_{j+1} W_{j+1} - n_j W_j). \tag{14}$$

where n_j and n_{j+1} are the sound power coefficients for sound sources placed at x_j and x_{j+1}, respectively, and they are integers.

Equation (13) represents the sound energy arriving at observation point P that originates from the virtual sound sources located in section j during the time interval from t to $t + d_0/2v$. In other words, Eq. (13) and Eq. (14) mean that the sound source in section X_{j+1} at time t was previously located in section X_j at $t - d_0/2v$, and the sound source contributes to the sound energy coming from the j-th section to point P during $d_0/2v$. In these equations c is the sound velocity (= 342 m/s). If $c \gg v$, the sound energy emitted by a virtual sound source located in section j is irrelevant to the source located in the $(j + 1)$-th section. Hence, in this case, the sound energy arriving at point P during the time interval between t and $t + d_0/2v$,

Table 1. Time that a sound arrives at the observation point at time t is emitted from the virtual point source and its energy emitted during $d_0/2v$ [s]

Place of virtual sound source	Time when sound is emitted	Sound energy emitted during $d_0/2v$ [s]
x_0	$\left(t-\frac{d_0}{c}\right)\sim\left(t-\frac{d_0}{c}+\frac{d_0}{2v}\right)$	$J_0=n_0W_0\frac{d_0}{2v}$
$x_{-1}\sim x_1$	$\left(t-\frac{d_0}{c}\sqrt{1+\frac{1}{4}}\right)\sim\left(t-\frac{d_0}{c}\sqrt{1+\frac{1}{4}}\right)+\frac{d_0}{2v}$	$J_{-1}=n_0W_0\frac{d_0}{c}\left(\sqrt{1+\frac{1}{4}}-1\right)+n_{-1}W_{-1}\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+\frac{1}{4}}-1\right)\right\}$, $J_1=n_2W_2\frac{d_0}{c}\left(\sqrt{1+\frac{1}{4}}-1\right)+n_1W_1\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+\frac{1}{4}}-1\right)\right\}$
$\vdots$	$\vdots$	$\vdots$
$x_{-j}\sim x_j$	$\left(t-\frac{d_0}{c}\sqrt{1+\frac{j^2}{4}}\right)\sim\left(t-\frac{d_0}{c}\sqrt{1+\frac{j^2}{4}}\right)+\frac{d_0}{2v}$	$J_{-j}=n_{-j+1}W_{-j+1}\frac{d_0}{c}\left(\sqrt{1+\frac{j^2}{4}}-1\right)+n_{-j}W_{-j}\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+\frac{j^2}{4}}-1\right)\right\}$, $J_j=n_{j+1}W_{j+1}\frac{d_0}{c}\left(\sqrt{1+\frac{j^2}{4}}-1\right)+n_jW_j\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+\frac{j^2}{4}}-1\right)\right\}$
$\vdots$	$\vdots$	$\vdots$
$x_{-12}\sim x_{12}$	$\left(t-\frac{d_0}{c}\sqrt{1+6^2}\right)\sim\left(t-\frac{d_0}{c}\sqrt{1+6^2}\right)+\frac{d_0}{2v}$	$J_{-12}=n_{-11}W_{-11}\frac{d_0}{c}\left(\sqrt{1+6^2}-1\right)+n_{-12}W_{-12}\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+6^2}-1\right)\right\}$, $J_{12}=n_{13}W_{13}\frac{d_0}{c}\left(\sqrt{1+6^2}-1\right)+n_{12}W_{12}\left\{\frac{d_0}{2v}-\frac{d_0}{c}\left(\sqrt{1+6^2}-1\right)\right\}$

$J_P(t;d_0/2v)$ is obtained by integrating the intensity of sound coming from each virtual sound source located in each effective section of the road.

3. SOUND INTENSITY AND SOUND PRESSURE LEVEL

3.1. Sound Power of each Virtual Sound Source at the Time $t-d_0/c$

In the aforementioned method, if the number and type of vehicles present in section ΔX_j at time $t-d_0/c$ is stochastically estimated, then the total sound power from the virtual sound source located at center x_j of the j-th section is also stochastically estimated by the following equation:

$$W_j=\frac{(n_p)_jW_p+(n_t)_jW_t}{(n)_j}=\left(\frac{n_p}{n}\right)_jW_p+\left(\frac{n_t}{n}\right)_jW_t$$

$$(j=-12,-11,\ldots,0,\ldots,11,12), \qquad (15)$$

where $(n_p)_j$ is the number of passenger cars, and $(n_t)_j$ is the number of heavy vehicles located in section ΔX_j, and $(n)_j$ is the total number of automobiles in ΔX_j, that is, $(n)_j=(n_p)_j+(n_t)_j$. W_p and W_t represent the average sound power of a passenger car and that of a heavy vehicle, respectively.

W_j is the average sound power emitted from automobiles situated in section ΔX_j, but obviously differs from the sound power $\overline{W}$ used to estimate the number of effective sections as well as from the average sound power $\overline{W}$ in Eq. (7). W_j in Eq. (15) takes a probabilistic value that varies with time according to the numbers of passenger cars and heavy vehicles present in ΔX_j at a given time, whereas $\overline{W}$ in Eq. (7) represents a certain constant value regardless of the time lapsed. Thus, Eq. (15) can be rewritten as:

$$(n)_jW=(nW)_j=(n_p)_jW_p+(n_t)_jW_t, \qquad (16)$$

where j equals $-12,-11,\ldots,0,\ldots,11$, or 12. With this modification, Eq. (13) can be expressed as:

$$J_j(t;d_0/2v)=(nW)_{j+1}\left(\frac{d_0}{c}\right)\left\{\sqrt{1+\left(\frac{j}{2}\right)^2}-1\right\}+(nW)_j\left\{\frac{d_0}{2v}-\left(\frac{d_0}{c}\right)\left(\sqrt{1+\left(\frac{j}{2}\right)^2}-1\right)\right\}. \qquad (17)$$

3.2. Sound Intensity and Sound Pressure Level Observed at Point P at Time t

From Eq. (12) and Eq. (17), sound intensity $I_P(t)$ to be measured for every average integration time $d_0/2v$ [s] at the observation point P is given by:

$$I_P(t)=\frac{2v}{d_0}J_P\left(t;\frac{d_0}{2v}\right)=\frac{2v}{d_0}\sum_{j=-12}^{12}\frac{J_j\left(t;\frac{d_0}{2v}\right)}{2\pi r_j^2} \quad [\text{W/m}^2], \qquad (18)$$

where $r_j^2=d_0^2\left(1+\frac{j^2}{4}\right)$. Hence, the sound pressure level at P can be expressed as:

$$L(t)=10\log_{10}\left(\frac{I_P(t)}{I_0}\right) \quad [\text{dB}], \qquad (19)$$

where I_0 is the reference sound intensity, $I_0=10^{-12}$ [W/m^2].

4. RESULTS AND DISCUSSION

4.1. Comparison Between the Measured and Calculated L_{pA}'s

To verify the validity of our mathematical model for road traffic noise, the A-weighted sound pressure level, L_{pA}, was measured at select observation points along a freeway and compared with the calculated one. Additionally, the measured and calculated cumulative frequency distributions of the A-weighted sound pressure levels were compared with each other.

4.1.1. Measurement of L_{pA}

The measurement was made along a freeway with two lanes and a straight and flat road. This model assumes that cars are traveling while maintaining a steady flow. The measurement site and time where traffic volume was 1,000 vehicles or fewer per hour was selected. L_{pA} was measured every second for 5 minutes. The traveling speed of every car V [km/h] was measured, and regardless of the time, the speed was within 100±10 km/h. The residual noise around the freeway was about 50 dB in the daytime and 40 dB in the night time.

4.1.2. Calculation of L_{pA}

L_{pA} at observation point P was calculated according to Eq. (19). The road was assumed to be a straight line. The

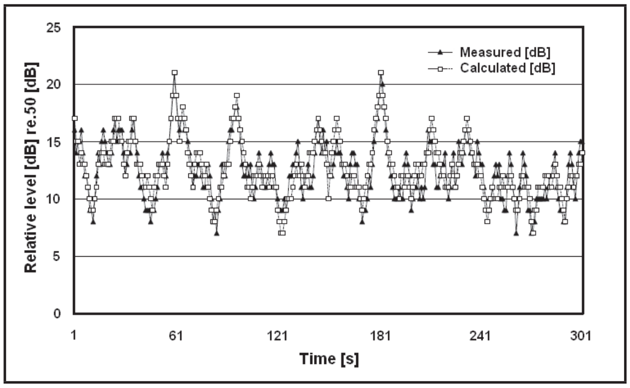

Figure 2. Daytime temporal variation of L_{pA} for 5 minutes at a point 56 m from the road.

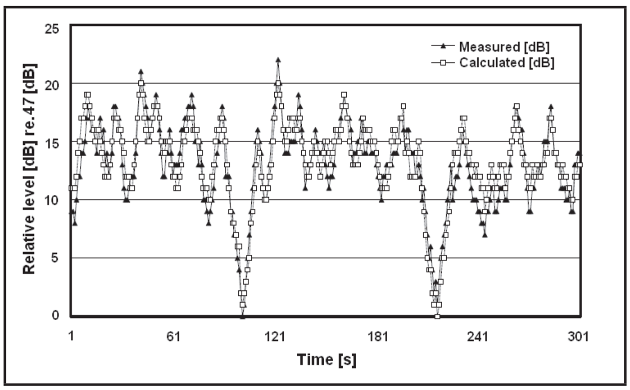

Figure 3. Nighttime temporal variation of L_{pA} for 5 minutes at a point 56 m from the road.

distance between two successive automobiles, the speed, and the sequence of them were equalized to those measured in the previous section. Similar to the previous section, the sampling and measurement time intervals were the same (1 second and 5 minutes, respectively). The power levels of a passenger car and a heavy vehicle were obtained by the following equation according to the method for estimating road traffic noise proposed by the Acoustical Society of Japan, ASJ Model 1993.

$$PWL = A^* \log_{10} V + B^* \quad \text{[dB]}, \tag{20}$$

where the regression coefficients A^* and B^* are referred to in the literature.[22]

Figure 2 sequentially shows the daytime measured and calculated data. The observation point was 56 m away from the freeway, and 50 dB was taken as the reference level (0 dB) for L_{pA}. Figure 3 denotes similar data for the nighttime, but the reference level was 47 dB. As both figures indicate, the calculated values are consistent with measured ones (within 2 dB).

4.2. Cumulative Frequency Distribution

To account for the fluctuation of the A-weighted sound pressure level due to changes in traffic volume with the time of day, Figs. 4–7 plot the cumulative frequency distributions. L_{pA} was calculated by the Monte Carlo simulation method based on Eq. (19).

The traffic volume corresponding to the cumulative frequency distribution shown in Fig. 4 was 837 vehicles/h, which consisted of 721 passenger cars and 116 heavy vehicles, and $d_0 = 50$ [m]. The measurement was conducted during the daytime. The percentile levels from this figure were $L_{50} = 65$ dB, $L_5 = 70$ dB, and $L_{95} = 62$ dB. Figure 5 shows the nighttime traffic volume. It consisted of 374 vehicles/h including 313 passenger cars and 61 heavy vehicles, yielding $L_{50} = 62$ dB, $L_5 = 69$ dB, and $L_{95} = 55$ dB.

Despite the nighttime traffic volume being considerably smaller than the daytime volume, the five percentile levels L_5 are similar. However, the interval between $L_5 - L_{95}$, which represents the fluctuation range, was 14 dB in the nighttime and 8 dB in daytime. This fact shows the difference in the nature of traffic at different times of day.

Figure 6 shows the daytime cumulative frequency distribution for the traffic volume of 777 vehicles/h, which consisted of 700 passenger cars and 77 heavy vehicles. Measurements were made at a point 100 m from the freeway. As seen from the figure, the percentile levels were $L_{50} = 62$ dB, $L_5 = 66$ dB, and $L_{95} = 59$ dB, and the range of fluctuation was 7 dB. Figure 7 shows the same information as Fig. 6 but for nighttime measurement. The traffic volume was 385 vehicles/h, which included 317 passenger cars and 68 heavy vehicles. In this case, $L_{50} = 59$ dB, $L_5 = 65$ dB, and $L_{95} = 53$ dB. By comparing Figs. 6 and 7, the range of fluctuation is 5 dB greater in the nighttime, although the five percentile levels are similar in both cases. The reason for the larger fluctuation range in the night may be due to the decreased traffic volume and the relative increase in the content rate of heavy vehicles. The fact that the five percentile level, L_5, does not change with the time of day suggests that it is determined by the number of times a heavy vehicle passes by and/or how many times two heavy vehicles pass by consecutively while maintaining the minimum allowable inter-vehicular distance, D_{min}. Additionally, the length of the time interval such a situation repeats may be noteworthy.[23]

4.3. Temporal Development of $L_{Aeq,\mathrm{1h}}$ in a Day

To further verify the validity of the mathematical model proposed in section 3, the A-weighted equivalent continuous sound pressure levels for an hour calculated according to Eq. (19) were compared with those measured consecutively during a 24-hour period.

4.3.1. Measurement of $L_{Aeq,\mathrm{1h}}$

The A-weighted equivalent sound pressure levels were measured for each hour over a 24-hour period. Measurements of the traffic volume, content, and speed of each car were executed at points 50 m and 100 m from the center line of a freeway. The traffic content was classified into two categories: passenger cars and heavy vehicles.

4.3.2. Method of Simulation Calculation

$L_{Aeq,\mathrm{1h}}$'s were calculated by a Monte Carlo simulation method based on Eq. (19). An exponentially random number as shown in Eq. (1) was adopted for traffic volume and the average inter-vehicular distance $\overline{D}$ [m], while a binominal random number was used to represent the traffic content rate of the two classification categories. These values were the same as those measured. The mean car speed $\overline{V}$ [km/h] and the distance from the center of the road to the observation point d_0

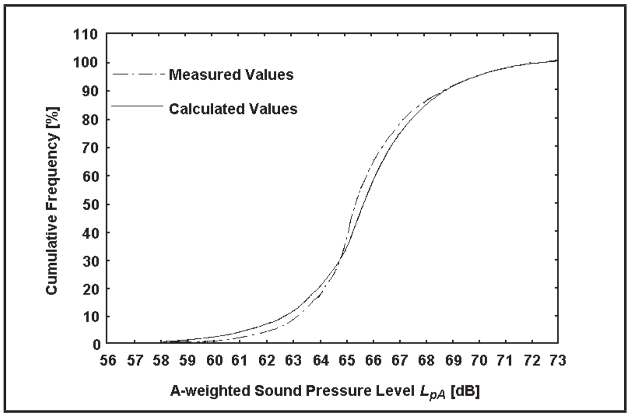

Figure 4. Daytime cumulative frequency distribution of L_{pA} at a point 50 m from the road.

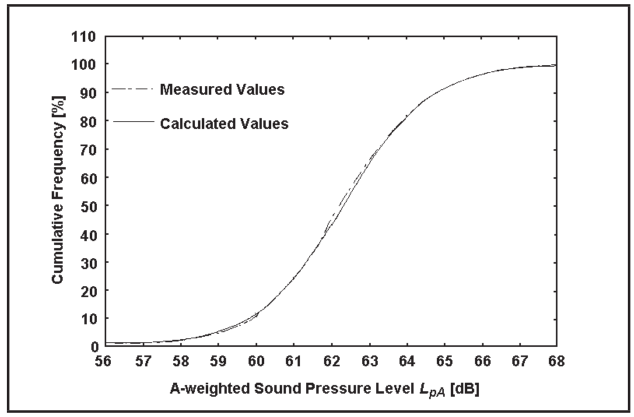

Figure 6. Daytime cumulative frequency distribution of L_{pA} at a point 100 m from the road.

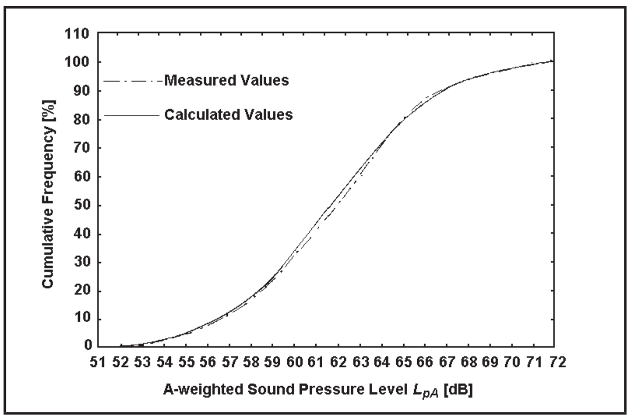

Figure 5. Nighttime cumulative frequency distribution of L_{pA} at a point 50 m from the road.

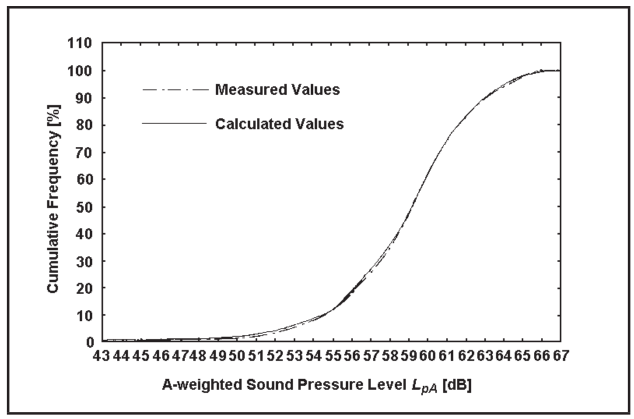

Figure 7. Nighttime cumulative frequency distribution of L_{pA} at a point 100 m from the road.

were also the same as those in the measurements. The simulation calculation was conducted for the minimum allowable distance, D_{min}, that corresponded to the mean speed, $\overline{V}$.

$L_{Aeq,T}$ is defined by:

$$L_{Aeq,T} = 10\log_{10}\left[\frac{1}{T}\int_0^T 10^{\frac{L_{pA}(t)}{10}}dt\right] \quad \text{[dB]}, \qquad (21)$$

where $L_{pA}(t)$ is the instantaneous A-weighted sound pressure level obtained from Eq. (19), and T is the measurement time interval. The authors have previously demonstrated that the ergodic theorem can be applied to $L_{pA}(t)$, if $L_{pA}(t)$ is a stationary stochastic process.[24,25] That is, in most cases, the temporal average for the probability distribution of $L_{pA}(t)$ is equal to its ensemble average. Thus, Eq. (21) can be rewritten as:

$$L_{Aeq,T} = 10\log_{10}\left\langle \exp\left(\frac{\ln 10}{10}L_{pA}(t)\right)\right\rangle \quad \text{[dB]}, \qquad (22)$$

where $\langle\cdot\rangle$ denotes the ensemble average. If T is 1 h, Eq. (22) can be replaced by the following cumulant expansion:

$$L_{Aeq,\text{1h}} = \gamma_1 + 0.115\gamma_2 + 0.0088\gamma_3 + 0.0005\gamma_4 + O(\gamma_5) \quad \text{[dB]}, \qquad (23)$$

where $\gamma_1 = m$, $\gamma_2 = \sigma^2$, $\gamma_3 = \overline{X'^3}$, $\gamma_4 = \overline{X'^4} - 3(\overline{X'^2})^2$, $X' = L_{pA}(t) - m$, and m and σ^2 denote the average and the variance for $L_{pA}(t)$, respectively.

To investigate the validity of road traffic noise models, measured $L_{Aeq,\text{1h}}$'s are compared with those calculated from Eq. (24), FHWA model, and ASJ RTN-Model 1993. Only traffic conditions and geometrical conditions were taken into account in the model estimations.

$L_{Aeq,T}$ is calculated by the following equation in STAMINA program for FHWA model:[14]

$$(L_{Aeq,\text{1h}})_i = \overline{L_{0i}} + 0.115\sigma_i^2 + 10\log_{10}\left(\frac{N_i\pi D_0}{TS_i}\right) + 10\log_{10}\left(\frac{D_0}{D}\right)^{1+\alpha} + 10\log_{10}\left(\frac{\psi_\alpha(\varphi_1,\varphi_2)}{\pi}\right) + \Delta_S \quad \text{[dB]}, \qquad (24)$$

where i designates each of three classes of vehicles, that is, passenger cars, medium trucks and heavy trucks. $\overline{L_{0i}}$ [dB] shows the averaged A-weighted sound pressure level of the noise from i-class vehicles at the reference distance, D_0 [m] (usually $D_0 = 15$ [m]). σ_i^2 is the variance of A-weighted sound pressure level of noise from class-i vehicle, and D is the observation distance. T is a measurement time interval (usually $T = 1$ h). N_i is the number of i-class vehicles passing by the observation point during measurement time interval, T, and S_i is their average vehicle speed. $\psi_\alpha(\varphi_1,\varphi_2)$ is the angle of the observation's view of a section of the road. Here $\psi_\alpha(\varphi_1,\varphi_2)$ is $\frac{163}{180}\pi$ rad. α is a site parameter, $0 < \alpha < 1$. α is taken as 0.4 for $D = 50$ m and 100 m. Δ_S is the excess attenuation due to obstacles such as barriers, buildings, and woods. In the present examination, Δ_S is 0.

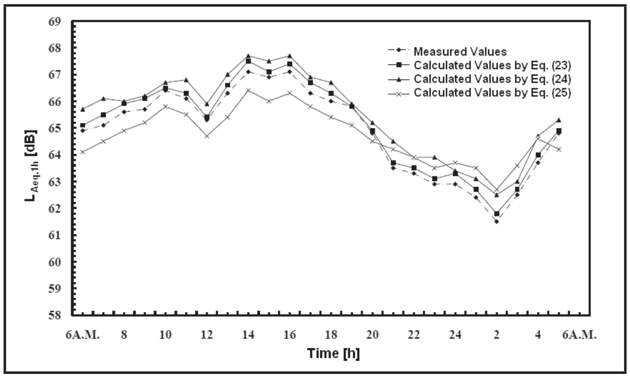

Figure 8. Temporal development of $L_{Aeq,1h}$ at a point 50 m from the road.

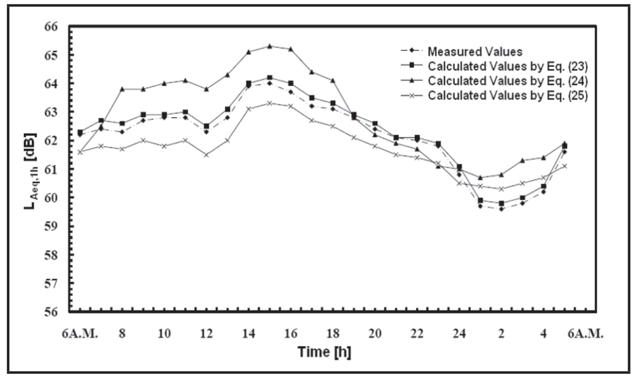

Figure 10. Temporal development of $L_{Aeq,1h}$ at a point 100 m from the road.

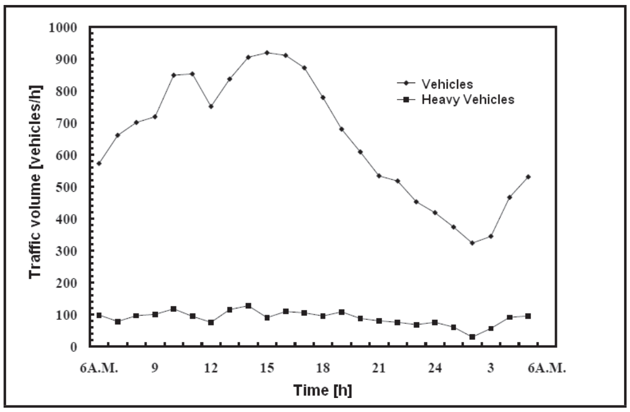

Figure 9. Temporal variation of traffic volume per hour and the number of heavy vehicles an hour corresponding to the measurement at $d_0 = 50$ m.

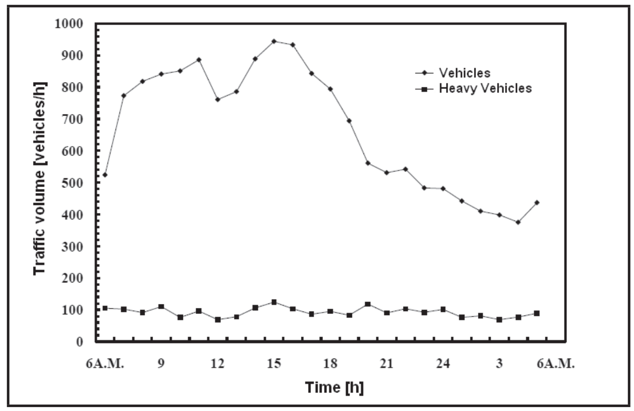

Figure 11. Temporal variation of traffic volume per hour and the number of heavy vehicles an hour corresponding to the measurement at $d_0 = 100$ m.

Furthermore, the calculated $L_{Aeq,1h}$'s from the simulation were compared with those obtained according to the estimation method proposed by the Acoustical Society of Japan, ASJ Model 1993. According to ASJ Model 1993, $L_{Aeq,1h}$ at the site along a road should be calculated for the range of car speed between 60 km/h and 120 km/h using the following equation:[20]

$$L_{Aeq,1h} = 10\log_{10} Q^* + 10\log_{10} V - 10\log_{10} d_0 + 32.1 \text{ [dB]}, \tag{25}$$

where Q^* represents the traffic volume calculated in terms of passenger cars by the following equation:

$$Q^* = (r_1 + Mr_2)Q \quad \text{[vehicles/h]}, \tag{26}$$

where r_1 and r_2 are the rate of passenger cars and that of heavy vehicles, respectively, $(r_1 + r_2 = 1)$. M is the number of passenger cars per each heavy vehicle in regard to noise emission, and here it is assumed to be 5.

Figure 8 shows the temporal development of calculated $L_{Aeq,1h}$'s at a point 50 m away from the road for a 24-hour period. As seen from the figure, $L_{Aeq,1h}$'s calculated from Eq. (23) are slightly higher than the measured values, but the difference is within 1 dB. $L_{Aeq,1h}$'s calculated according to Eq. (24) exceed the values estimated from Eq. (23) throughout the 24-hour period. On the other hand, $L_{Aeq,1h}$'s estimated by Eq. (25) are about 1 dB or more lower than the daytime measurements, but they are higher than the nighttime measurements. Thus, the results obtained by the model proposed in this paper coincide well with those measured.

Figure 9 plots the measured traffic volume per hour and the number of heavy vehicles for a 24-hour period. The maximum volume exceeds 900 vehicles/h in the day and the minimum volume is about 300 vehicles/h at night. The latter is about one-third of the former. Figure 10 shows the measured and calculated $L_{Aeq,1h}$'s at a point 100 m from the road on a different day. Similarly, the calculated $L_{Aeq,1h}$'s are in keeping with measured ones (within 1 dB). Most $L_{Aeq,1h}$'s estimated from Eq. (24) exceed the observed values by 1.0–1.6 dB, except for the time intervals between hours 19 and 23. In contrast, most of $L_{Aeq,1h}$'s calculated by Eq. (25) are lower by 1.0–1.6 dB compared with the measured values, except for the values calculated between hours 23 and 04. Figure 11 denotes the traffic volume during the measurement at the 100 m point. The maximum traffic volume exceeds 900 vehicles/h, while the minimum is about 300 vehicles/h in this case. From Figs. 8 and 10, the range of fluctuation in $L_{Aeq,1h}$'s is about 4–6[dB], but varies somewhat according to traffic conditions. Both Figs. 9 and 11 demonstrate that the number of passenger cars changes greatly according to the time of day, but that the number of heavy vehicles is nearly independent of time. Consequently, the rate of content of heavy vehicles increases at night, which explains why the $L_{Aeq,1h}$ values do not fall below about 59 to 60 dB.

5. CONCLUSIONS

As shown in Eqs. (17)–(19), the mathematical models proposed herein are expressed in the form of the recurrence formula with comparatively fewer variable factors. When obstacles in the sound propagation path are not present, level fluctuation of noise from a straight and flat freeway can be simulated easily and precisely using our models.

A-weighted sound pressure levels, L_{pA}, measured 56 m away from a freeway for 5 minutes in the daytime and nighttime are in keeping with those calculated by Eq. (19) (within 2 dB).

The cumulative frequency distributions of L_{pA} measured 50 m and 100 m from a freeway coincide well with those calculated according to Eq. (19).

Levels of $L_{Aeq,1h}$ calculated based on the mathematical model proposed in this paper agree exceedingly well (within 1 dB) with those measured even for a small traffic volume below 1,000 vehicles/h.

The nighttime range in the level fluctuation is far greater than in the daytime because the traffic volume decreases markedly at night despite the nearly constant number of heavy vehicles passing.

6. DISCUSSION

Because road traffic noise has a time-varying nature as mentioned in the introduction, a static model cannot sufficiently estimate the influence of road traffic noise on the community. Thus, it is sometimes necessary to consider the fluctuation in the sound level. Actual traffic conditions change with time, and accordingly the appearance rate of the maximum L_{pA} and $L_{Aeq,T}$ for a short time interval should vary with time. The dynamic model, which explicitly represents the fluctuating characteristic, may be indispensable for estimating the influence of road traffic noise, especially from a road with light traffic on a community.[23]

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