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A FUNDAMENTAL STUDY FOR PREDICTING THE URBAN STREET NOISE BY USE OF THE IMAGE METHOD APPROACH

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This paper describes a unified statistical method of structural prediction of an arbitrarily fluctuating street noise in the general urban noise environment, especially from a fundamental viewpoint. That is, an analytical expression of the noise propagation characteristics for several cases of typically idealized road traffic models is first derived, in order to express an actual noise environment in the city area, based on the image method approach. Then, by using the newly derived expression of the noise propagation characteristics, two representative evaluation indices of street noise, closely related to the well-known L_{eq} and L_{NP} evaluation indices, can be given in an explicit functional form with several internal mechanisms of the road traffic environments in the city area. Finally the validity of the present theoretical prediction method is experimentally confirmed, especially by use of digital simulation technique for several cases of typically idealized actual road traffic noise environment in the city area.

1. Introduction

In recent years, problems of environmental noise generated by passing transportation vehicles in the city area have become more critical, owing to the hasty popularization of the traffic means in our daily life.

Especially in the city area with complex geometrical structures, such as a single-level intersection, a grade-separated intersection or a multi-lane road etc., the question of analysis of the actual noise environment has not yet been theoretically solved in principle because of the arbitrariness of the movement of noise sources and the complicated situation of actual noise propagation paths. Nevertheless, based on the consideration that the environmental random noise phenomena are dominantly caused by the transportation vehicles passing in the city area, a realistic approach to structural evaluation of the effect of the noise generated by these passing vehicles on the resultant environmental noise level, in a functional form with the noise propagation characteristics, is fundamentally important. Before the establishment of new buildings and roads, prediction of this noise effect should be investigated, from the viewpoint of noise control for town planning.

From the above circumstances, in this paper, a fundamental theory of statistical prediction of the general street noise level over a complicated actual city traffic environment is derived, based on the well-known image method approach [1]. More concretely, after expressing the noise propagation characteristic between the noise sources and the observation point over the city area in an explicit functional form by use of the image method approach, a unified statistical method of structural prediction of the arbitrarily fluctuating street noise in several typical cases of the urban noise environment is first derived. Among various evaluation indices of the actual urban noise environment, especially two evaluation indices, closely related to the well-known L_{eq} and L_{NP} [2], can be given in an analytical form with the internal mechanisms of traffic environment.

In view of the complexity of the statistical prediction and the variety of forms of level distribution of urban road traffic noise, the technique of digital simulation seems to be the most powerful and effective way of experimental confirmation. The validity of the prediction method proposed was principally confirmed especially by use of the digital simulation technique for several cases of typically idealized actual road traffic noise environment in the city area, since this kind of study is in an early stage.

2. Explicit expressions of the noise propagation characteristic in the city area

By considering a well-known fact that the urban noise problem is originally caused by a rapid increase in the number of noise sources, such as transportation vehicles, motorcycles etc., and the swift gravitation of the population to the city area, it is necessary to describe first several fundamental models of typical noise environment in the city area, such as a straight road and other different intersections. Then, the actual circumstances in the city area can be analyzed as a complicated composition of these models of typical noise environment.

2. 1. Noise propagation characteristic in the city area with a straight road (*Case 1*)

Let us consider a straight road with the arbitrary segment $[-L, L]$ and the arbitrary width L_x. It is assumed that an arbitrarily passing vehicle S moves in the middle of the road and an observation point O is placed on the sidewalk by the road, at a distance X from the passing vehicle along the road, as shown in Fig. 1a.

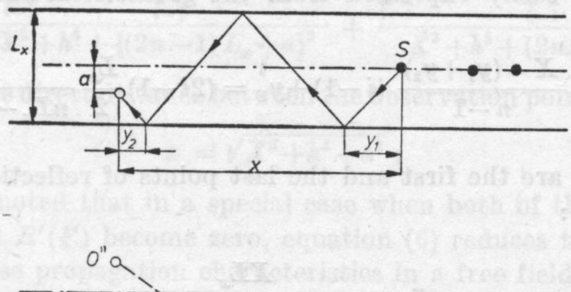

Fig. 1. Analysis of noise propagation characteristics for the straight road model. a) Noise propagation for the straight road, b) Analysis of noise propagation to image observers based on the image method approach

The noise intensity I at the observation point O, generated by the passing vehicle S, is generally expressed by the sum of the direct noise intensity I_1 and the reflected noise intensity I_2:

$$I = I_1 + I_2. \tag{1}$$

Hereupon, by use of the inverse-square law of noise propagation, the direct noise intensity I_1 can be expressed as:

$$I_1 = \frac{QW}{4\pi(X^2 + h^2 + a^2)}, \tag{2}$$

where h denotes the difference of height between the observation point and the noise source. Moreover, Q is a directivity factor and W is the acoustic power generated by the passing vehicle.

The reflected noise intensity due to the surrounding buildings lined along each side of the road can be evaluated by regularly assuming image observers at a place perpendicular to the road, as shown in Fig. 1b, on the basis of the image method approach. In the case when the noise wave reflects n times from the surrounding buildings, the distance X_i between the ith reflection point and the noise is easily expressed from the geometrical analysis $(1 < i < n)$:

$$X_i \triangleq \Delta \frac{X-(y_1+y_2)}{n-1}(i-1)+y_1 = (2i-1)\frac{L_x}{2}\frac{X}{nL_x-(-1)^n a}, \tag{3}$$

where y_1 and y_2 are the first and the last points of reflection from the noise source, given as:

$$y_1 = \frac{XL_x}{2(nL_x-(-1)^n a)}, \qquad y_2 = \frac{X\left(\frac{L_x}{2}-(-1)^n a\right)}{nL_x-(-1)^n a}. \tag{4}$$

Let $R(\xi)$ and $R'(\xi')$ be the reflection coefficients of the building surfaces along each side of the road at the points ξ and ξ'. Then, by considering these acoustical and geometrical parameters of noise environment, the received noise intensity L_2 can be expressed, based on the additivity of energy quantity:

$$I_2 = \frac{QW}{4\pi}\sum_{n=1}^{\infty}\left[\frac{\prod_{i=1}^{n-1}R(X_{2i})\prod_{i=1}^{n}R'(X_{2i-1})}{X^2+h^2+\{(2n-1)L_x-a\}^2} + \frac{\prod_{i=1}^{n}R(X_{2i})\prod_{i=1}^{n}R'(X_{2i-1})}{X^2+h^2+(2nL_x+a)^2} + \frac{\prod_{i=1}^{n-1}R'(X_{2i})\prod_{i=1}^{n}R(X_{2i-1})}{X^2+h^2+\{(2n-1)L_x+a\}^2} + \frac{\prod_{i=1}^{n}R'(X_{2i})\prod_{i=1}^{n}R(X_{2i-1})}{X^2+h^2+(2nL_x-a)^2}\right]. \tag{5}$$

Substituting equations (2) and (5) into equation (1), one can easily obtain the following expression of the noise propagation characteristics between the observation point O and the arbitrarily passing vehicle S:

$$f(x)=f(\sqrt{X^2+h^2+a^2})=\frac{1}{4\pi(X^2+h^2+a^2)}+$$

$$+\frac{1}{4\pi}\sum_{n=1}^{\infty}\left[\frac{\prod_{i=1}^{n-1}R(X_{2i})\prod_{i=1}^{n}R'(X_{2i-1})}{X^2+h^2+\{(2n-1)L_x-a\}^2}+\frac{\prod_{i=1}^{n}R(X_{2i})\prod_{i=1}^{n}R'(X_{2i-1})}{X^2+h^2+(2nL_x+a)^2}+\right.$$

$$\left.+\frac{\prod_{i=1}^{n-1}R'(X_{2i})\prod_{i=1}^{n}R(X_{2i-1})}{X^2+h^2+\{(2n-1)L_x+a\}^2}+\frac{\prod_{i=1}^{n}R'(X_{2i})\prod_{i=1}^{n}R(X_{2i-1})}{X^2+h^2+(2nL_x-a)^2}\right], \tag{6}$$

where x means the direct distance between the observation point and the vehicle:

$$x=\sqrt{X^2+h^2+a^2}. \tag{7}$$

It should be noted that in a special case when both of the reflection coefficients $R(\xi)$ and $R'(\xi')$ become zero, equation (6) reduces to the well-known expression of noise propagation characteristics in a free field of sound. In addition, when both of the reflection coefficients can be approximated in the following same functional form:

$$R(\xi)=R'(\xi')\simeq\exp(-\varepsilon), \tag{8}$$

one can obtain more useful expressions of noise propagation characteristics for practical use. That is, in this case, the following approximation is derived:

$$\prod_{i=1}^{n}R(X_i)=\exp(-n\varepsilon). \tag{9}$$

Therefore, substituting the above relation into equation (6), one can obtain the following explicit expression of the noise propagation characteristics:

$$f(x)=\frac{1}{4\pi(X^2+h^2+a^2)}+\frac{1}{4\pi}\sum_{n=1}^{\infty}\left[\frac{\exp(-n\varepsilon)}{X^2+h^2+\{nL_x+(-1)^n a\}^2}+\right.$$

$$\left.+\frac{\exp(-n\varepsilon)}{X^2+h^2+\{nL_x-(-1)^n a\}^2}\right]\overset{\Delta}{=}f_0(x). \tag{10}$$

From the practical point of view, equation (10) can be more simplified in the following two actual cases, in a compact form of expression.

a) Approximate expression of the noise propagation characteristics with a high reflection coefficient of the building surfaces

In a case when the surrounding buildings have high reflection coefficients of sound (i.e., their reflection coefficients become nearly equal to one), an approximate explicit expression of the noise propagation characteristics in the city area with a straight road can be expressed as:

$$f(x) \simeq \frac{1-\exp(-\varepsilon)}{4\pi(X^2+h^2+a^2)} + \frac{\exp(-\varepsilon)}{8L_x}\left[\frac{\sinh\left(\frac{\pi}{L_x}\sqrt{X^2+h^2}\right)}{\sqrt{X^2+h^2}\left\{\cosh\left(\frac{\pi}{L_x}\sqrt{X^2+h^2}\right)-\cos\left(\frac{\pi a}{L_x}\right)\right\}} + \frac{\sinh\left(\frac{\pi}{L_x}\sqrt{X^2+h^2}\right)}{\sqrt{X^2+h^2}\left\{\cosh\frac{\pi}{L_x}\sqrt{X^2+h^2}-\cos\left(\frac{\pi(L_x+a)}{L_x}\right)\right\}}\right] \stackrel{\Delta}{=} f_1(x). \quad (11)$$

b) Approximate expression of the noise propagation characteristics with a low reflection coefficient of the building surfaces

In the case when the surrounding buildings have low relection coefficients of sound (i.e., they have highly absorptive surfaces, so that their reflection coefficients become nearly equal to zero), an approximate explicit expression for this case can be expressed as:

$$f(x) \simeq \frac{1}{4\pi(X^2+h^2+a^2)} + \frac{\sum_{n=1}^{\infty}\exp(-n\varepsilon)}{4\pi}\left[\frac{1}{X^2+h^2+(L_x+a)^2} + \frac{1}{X^2+h^2+(L_x-a)^2}\right] = \frac{1}{4\pi(X^2+h^2+a^2)} + \frac{1}{4\pi}\frac{\exp}{1-\exp}\times$$

$$\times\left[\frac{1}{X^2+h^2+(L_x+a)^2} + \frac{1}{X^2+h^2+(L_x-a)^2}\right] \stackrel{\Delta}{=} f_2(x). \quad (12)$$

2.2. Noise propagation characteristics in the city area with a T-type intersection (Case 2)

Now, let us consider the noise propagation characteristics in a case when the passing vehicle is located within the intersection, as shown in Fig. 2. In this case, the geometrical condition for noise reflections is given under the restriction that the sound wave should be reflected first at the corner of the intersection, i.e.;

$$y_1 > X - X_0, \quad (13)$$

where X_0 is the distance between the observation point and the corner. Furthermore, y_1 is the distance between the passing vehicle S and the first reflection point, as shown in Fig. 2.

Therefore, the noise propagation characteristics of the T-type intersection can be expressed as follows:

$$f(x) = \frac{1}{4\pi(X^2+h^2+a^2)} + \frac{1}{4\pi}\sum_{n=1}^{n_1} \frac{\exp(-n\varepsilon)}{X^2+h^2+\{nL_x+(-1)^n a\}^2} + \\ + \frac{1}{4\pi}\sum_{n=1}^{n_2} \frac{\exp(-n\varepsilon)}{X^2+h^2+\{nL_x-(-1)^n a\}^2}. \quad (14)$$

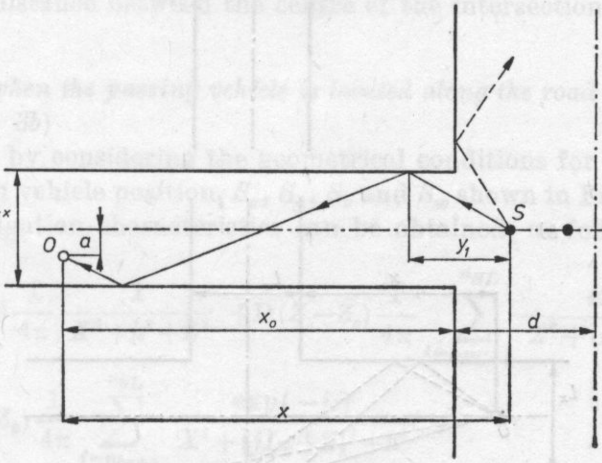

Fig. 2. Analysis of noise propagation characteristics for the T-type intersection

In equation (14), the maximum numbers, n_1 and n_2, of the repeated reflections are limited, due to the finite length of the building rows along the street. That is, the two numbers, n_1 and n_2, in equation (14) can be evaluated as:

$$n_1 \triangleq \max\left\{2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)} - \frac{a}{L_x}\right)\right], 2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)} + \frac{a}{L_x}\right) - 1\right] + 1\right\},$$

$$n_2 \triangleq \max\left\{2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)} + \frac{a}{L_x}\right)\right], 2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)} - \frac{a}{L_x}\right) - 1\right] + 1\right\}. \quad (15)$$

with Gauss' symbol [.]. In the case when the passing vehicle is located along the building rows, it is needless to say that the explicit expression of the noise propagation characteristics is given by equation (6).

2.3. *Noise propagation characteristics in the city area with a crossroads* (*Case 3*)

In a case when a passing vehicle is located within the intersection as shown in Fig. 3, one can consequently obtain the explicit expression of the noise propagation characteristics, based on the same analysis method as that described in the previous section.

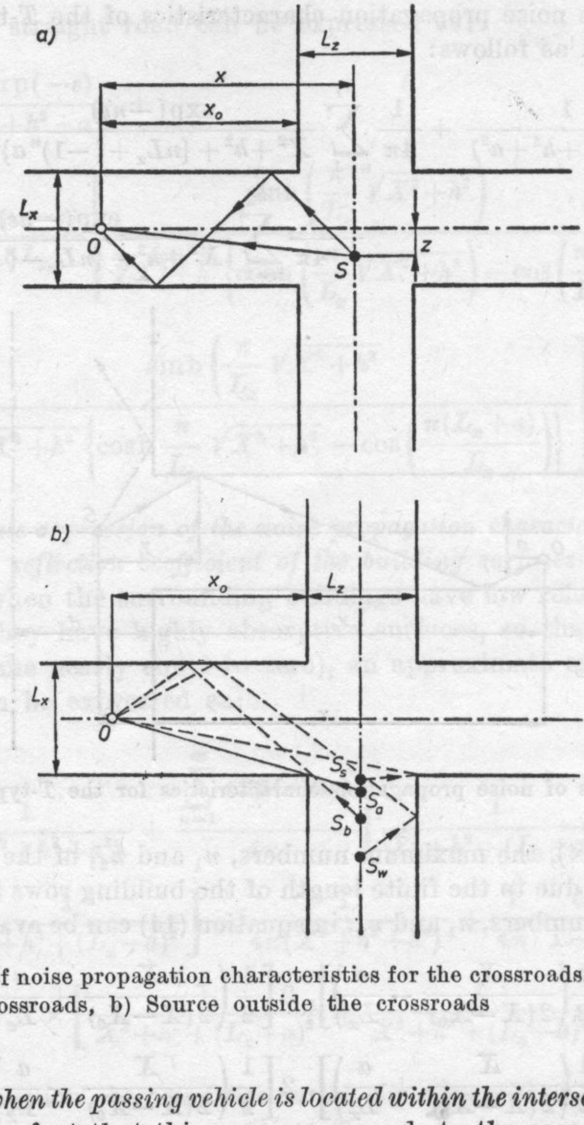

Fig. 3. Analysis of noise propagation characteristics for the crossroads. a) Source inside the crossroads, b) Source outside the crossroads

a) The case when the passing vehicle is located within the intersection (*see Fig.* 3*a*)

In view of the fact that this case corresponds to the case when the passing vehicle is located within a T-type intersection, the explicit expression of the noise propagation characteristics is expressed as follows:

$$f(x) = \frac{1}{4\pi(X^2+Z^2+h^2)} + \frac{1}{4\pi}\sum_{n=1}^{n_1} \frac{\exp(-n\varepsilon)}{X^2+(nL_x-Z)^2+h^2} + \frac{1}{4\pi}\sum_{n=1}^{n_2} \frac{\exp(-n\varepsilon)}{X^2+(nL_x+Z)^2+h^2}, \tag{16}$$

with

$$n_1 \triangleq \max\left\{2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)}-\frac{Z}{L_x}\right)\right], 2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)}+\frac{Z}{L_x}\right)-1\right]+1\right\},$$

and (17)

$$n_2 \triangleq \max\left\{2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)}+\frac{Z}{L_x}\right)\right], 2\left[\frac{1}{2}\left(\frac{X}{2(X-X_0)}-\frac{Z}{L_x}\right)-1\right]+1\right\}.$$

where Z is the distance between the centre of the intersection and the vehicle position.

b) The case when the passing vehicle is located along the road outside the intersection (see Fig. 3b)

In this case, by considering the geometrical conditions for the noise reflections due to each vehicle position, S_s, S_a, S_b and S_w shown in Fig. 3b, the objective noise propagation characteristics can be obtained, as follows:

$$f(x) = D(Z_d-Z)\frac{1}{4\pi}\frac{1}{X^2+h^2+Z^2}+D(Z-Z_s)\frac{1}{4\pi}\sum_{i=n_{SS+1}}^{n_{SL}}\frac{\exp(-i\varepsilon)}{Z^2+(iL_Z+X)^2+h^2}+$$

$$+D(Z-Z_b)\frac{1}{4\pi}\sum_{j=n_{bS+1}}^{n_{bL}}\frac{\exp(-j\varepsilon)}{X^2+(jL_x+Z)^2+h^2}+$$

$$+D(Z-Z_{WB})\sum_{n=1}^{\infty}\left\{\frac{1}{4\pi}\sum_{t=h_{WC+1}}^{n_{WB}}\frac{\exp[-(n+t)\varepsilon]}{(X+tL_z)^2+(nL_x+Z)^2+h^2}+\right.$$

$$+D(Z-Z_{WA})\sum_{n=1}^{\infty}\left\{\frac{1}{4\pi}\sum_{t=h_{WC+2}}^{n_{WA}}\frac{\exp[-(n+t)\varepsilon]}{(X+tL_z)^2+(nL_x+Z)^2+h^2},\right. \quad (18)$$

where each symbol is given by:

(19)

$$Z_d=\frac{L_x}{2}\left(1+\frac{L_z}{2X_0},\quad Z_s=\frac{L_x}{2}\left(\frac{L_z}{2(L_z+X_0)}+1\right),\quad Z_b=\frac{L_x}{2}\left(\frac{L_z}{2X^0}-1\right),\right.$$

$$Z_{WA}=\frac{L_x}{2}\left(\frac{3(2n-1)L_z}{2X_0}-\frac{1}{2}\right),\quad Z_{WB}=\frac{L_x}{2}\left(\frac{(2n+1)L_z}{2(X_0+L_z)}+\frac{1}{2}\right),\quad n_{SL}$$

$$=\left[\frac{X_0(2Z-L_x)}{L_xL_Z}-\frac{1}{2}\right],\quad n_{SS}=\left[\frac{X_0(2Z-L_x)}{L_xL_Z}+\frac{2Z}{L_x}-\frac{1}{2}\right],\quad n_{bS}$$

$$=\left[\frac{X_0(2Z-L_x)}{L_xL_Z}-\frac{1}{2}\right],\quad n_{bL}=\left[\frac{X_0 2(Z+L_x)}{L_xL_Z}-\frac{1}{2}\right],\quad n_{WA}$$

$$= \left[\frac{X_0(2Z+L_x)}{(2n-1)L_xL_Z} - \frac{1}{2} \right], \quad n_{WB} = \left[\frac{(X_0+L_z)(2Z-L_x)}{(2n+1)L_xL_Z} + \frac{1}{2} \right], \quad n_{WC} = \left[\frac{X_0(2Z-L_x)}{(2n+1)L_xL_Z} - \frac{1}{2} \right].$$

In the above expression, $D(.)$ denotes the truncation function defined as

$$D(\xi) = \begin{cases} 0 & (\xi) \leqslant 0), \\ 1 & (\xi) > 0). \end{cases} \tag{20}$$

3. Establishment of the model of the road traffic noise in the city area

As a noise environment model, a main road in the city area having a complex structure with building rows on the both sides is generally considered in this section.

From the additivity of noise energy, the noise intensity I at an observation point along the road is generally expressed as follows:

$$I = \sum_{j=1}^{J} \sum_{i=1}^{n_j} QW_{ij} f(X_{ij}) + v, \tag{21}$$

where J denotes the number of different vehicle-types and n_j is the number of the jth vehicle-type. Also, X_{ij} is the distance between the ith vehicle and the observation point, W_{ij} is the acoustic power generated by the ith vehicle and Q is a directivity factor. Moreover, v denotes the intensity of the backgro-und noise.

Let us introduce the following assumptions based on the actual situation of traffic flow:

1) The total number of vehicles passing through the road segment under consideration is governed by the following well-known Poisson distribution [3]:

$$P(n) = \frac{1}{n!} \exp(-N_0) N_0^n. \tag{22}$$

Hereupon, N_0 denotes the mean value of the total vehicle number.

2) The probability distribution function of the number of each vehicle-type is given by the following multi-nomial distribution [4]:

$$P(n_1, n_2, \ldots, n_J | n) = \frac{n!}{n_1!\, n_2! \ldots n_J!} \theta_1^{n_1} \theta_2^{n_2} \ldots \theta_J^{n_J}. \tag{23}$$

In the above expression, $\theta_j (j = 1, 2, \ldots, J)$ denotes the intermixture ratio of the jth vehicle-type.

3) The position of each vehicle occupies independently, X_{ij}, and its probability distribution function is a well-known uniform distribution.

Based on these assumptios made with respect to the traffic flow and the previously derived explicit expressions of the noise propagation characteristics in the city area, let us consider two important representative evaluation indices L_1 and L_2, related to L_{eq} and L_{NP}, among several evaluation indices of the environmental noise. Since it is well-known that L_{eq} is closely related to the averaged noise intensity λ_1, the first evaluation index is adopted as follows:

$$L_1 = 10\log_{10}(\lambda_1/W_0), \tag{24}$$

where W_0 is equal to $10^{-12} W/m$.

On the other hand, in relation to the fact that the widely used evaluation index L_{NP} is defined as $L_{NP} = L_{eq} + 2.56\,\sigma$($\sigma^2$ being the variance of the noise level fluctuation), the second evaluation index is adopted as follows:

$$L_2 = 10\log_{10}(\lambda_2/W_0^2), \tag{25}$$

where λ_2 is the variance of the noise intensity fluctuation.

Hereupon, it must be noticed that there is no redundancy of information between λ_1 and λ_2, in constant to the relation between L_{eq} and σ in the definition of L_{NP}.

Accordingly, in order to derive the unified expressions of the above two indices L_1 and L_2, the nth order cumulant of noise intensity fluctuation should first be found in an analytical form. Thus, the moment generating function $g(s)$ of the noise intensity fluctuation I can be derived under the above three assumptions made on the traffic flow and the concrete information on the noi se propagation characteristics, as follows:

$$g(s) \overset{\Delta}{=} \langle \exp(sI)\rangle_I = \left\langle \left\langle \left\langle \exp\left(s \sum_{j=1}^{J} \sum_{i=1}^{n_j} QW_{ij} f(X_{ij}) + sv\right)\right\rangle_{W_{ij}, X_{ij} v | n_j, n} \right\rangle_{n_j | n} \right\rangle_n, \tag{26}$$

where $\langle \cdot \rangle *$ denotes an expectation operation with respect to the random variable $*$. Hereupon, paying one's attention to the property of statistical independency between the background noise and the road traffic noise, and a multinomial distribution on the number of each vehicle-type, equation (26) can be rewritten, as follows:

$$g(s) = \Big\langle \sum_{n_1+n_2+\dots+n_J=n} \frac{n!}{n_1!\,n_2!\dots n_J!} \prod_{j=1}^{J} \{Q_j\}\, n_j \times$$

$$\times \langle \exp[s_1 QW_{ij} f(X_{ij}) n_j]\rangle_{Wi_j, Xi_j} \Big\rangle n\, \langle \exp(sv)\rangle_v$$

$$= \left\langle \left\{ \sum_{j=1}^{J'} \theta_j \langle \exp[sQW_{ij} f(X_{ij})]\rangle_{W_{ij}, X_{ij}} \right\}^n \right\rangle_n \langle \exp(sv)\rangle_v. \tag{27}$$

Furthermore, from the property of Poisson distribution on the total number of vehicle, the moment generating function can be finally expressed as follows:

$$g(s) = \sum_{n=0}^{\infty} \frac{1}{n!} \exp(-N_0)\{N_0\}^n \Big\{ \sum_{j=1}^{J} \theta_j \langle \exp[sQW_{ij} f(X_{ij})] \times \rangle_{W_{ij}, X_{ij}} \Big\}^n \langle \exp(sv) \rangle_v$$

$$= \exp\Big[N_0 \sum_{n=1}^{\infty} \frac{s^n}{n!} \sum_{j=1}^{J} \theta_j \langle (QW_{ij})^n \rangle_{W_{ij}} \langle f^n(X_{ij}) \rangle X_{ij}\Big] \times \langle \exp(sv) \rangle_v. \quad (28)$$

Thus, the nth order cumulant λ_n of the noise intensity fluctuation I can be generally derived as follows:

$$\lambda_n = N_0 \sum_{j=1}^{J} \theta_j \langle (QW_{ij})^n \rangle_{W_{ij}} K_{fn} + \psi_n, \quad (29)$$

where ψ_n denotes the nth order cumulant of only the background noise intensity and K_{fn} denotes the following nth order moment related to the noise propagation characteristics $f(X_{ij})$:

$$K_{fn} \triangleq \langle f^n(X_{ij}) \rangle_{X_{ij}} = \int_{-L}^{L} f^n(X_{ij}) P(X_{ij}) dX_{ij}. \quad (30)$$

Substituting equation (29) into the definition of the two adopted evaluation indices L_1 and L_2, one can as a result obtain the explicit expressions of the two objective indices, as follows:

$$L_1 = 10\log_{10}\Big(\frac{1}{W_0}\Big\{N_0 \sum_{j=1}^{J} \theta_j \langle QW_{ij} \rangle_{W_{ij}} \langle f(X_{ij}) \rangle_{X_{ij}} + \psi_1\Big\}\Big), \quad (31)$$

$$L_2 = 10\log_{10}\Big(\frac{1}{W_0^2}\Big\{N_0 \sum_{j=1}^{J} \theta_j \langle Q^2 W_{ij}^2 \rangle_{W_{ij}} \langle f^2(X_{ij}) \rangle_{X_{ij}} + \psi_2\Big\}\Big). \quad (32)$$

From the analytical expressions shown in equations (31) and (32), and the explicit expressions of noise propagation characteristics, one can evaluate an actual noise environment in the city area by using information on the traffic flow and the geometrical and acoustical parameters of the circumstances.

4. Experimental considerations

In this section, paying special attention to the urban noise environment with a straight road, the validity of the proposed theoretical results was confirmed experimentally by use of the digital simulation technique, in view of the arbitrariness of the fluctuating patterns and the complicated situation of the noise phenomena. Let us consider a straight road with building rows along each side of the road, as shown in Fig. 4. The observation point is placed on the sidewalk at the distance $a(0 < a < L_x/2)$. The passing vehicles in the segment $[-L, L]$ of the road are considered, under the following assumptions:

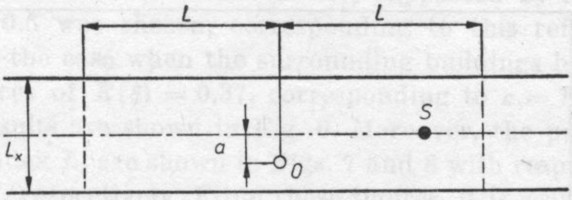

Fig. 4. Straight road model

1) Vehicles passing in the road are composed of two vehicle-types, a light vehicle-type and a heavy vehicle-type, with $J = 2$. The number n_j of passing vehicles of the jth vehicle-type is generated by use of random numbers of a multinomial distribution with the intermixture ratios of the jth vehicle-type: $\theta_1 = 0.8$ and $\theta_2 = 0.2$.

2) Each vehicle in the same vehicle-type generates a constant acoustic power. As is well-known, the ratio of two acoustic powers generated by a heavy vehicle-type and a light vehicle-type is ten to one, according to an empirical value recommended by the Acoustical Society of Japan.

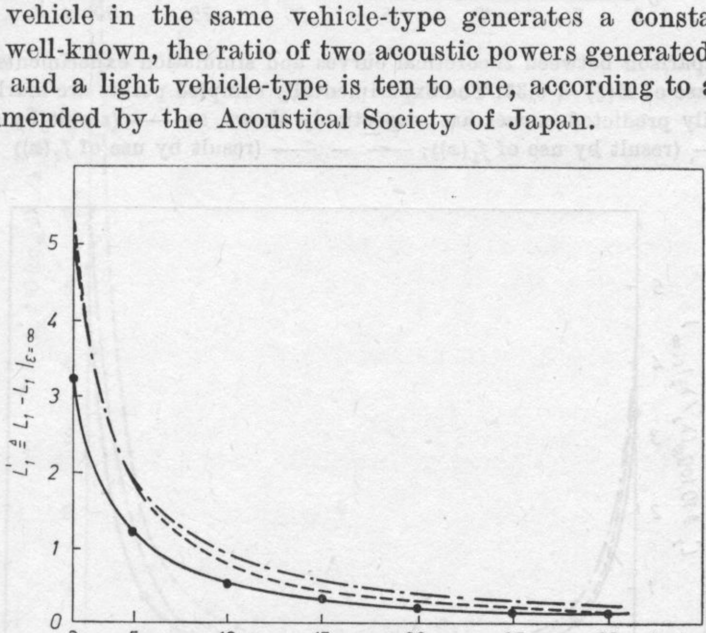

Fig. 5. A comparison between theoretical curves and simulation experiments with respect to L_1, in the case of $R(\xi) = 0.61$. The experimentally sampled points are marked by $\cdot$, and the theoretically predicted curves are respectively shown as —— (result by use of $f_0(x)$); — — — — — (result by use of $f_1(x)$); —— — —— (result by use of $f_2(x)$)

In order to show the difference between an urban noise environment and a rural noise one, the difference between the characteristic indices in these two typical environments was considered. Also, for the purpose of unifying the experimental situation between the road width L_x and the distance a, the ratio L_x/a was employed for the horizontal axis in each figure.

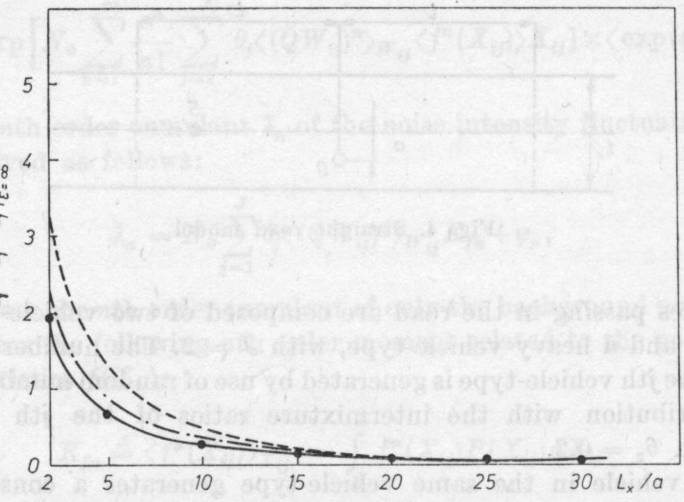

Fig. 6. A comparison between theoretical curves and simulation experiments with respect to L_1, in the case of $R(\xi) = 0.37$. The experimentally sampled points are marked by $\cdot$, and the theoretically predicted curves are respectively shown as —— (result by use of $f_0(x)$); — — — — — (result by use of $f_1(x)$); —— — —— (result by use of $f_2(x)$)

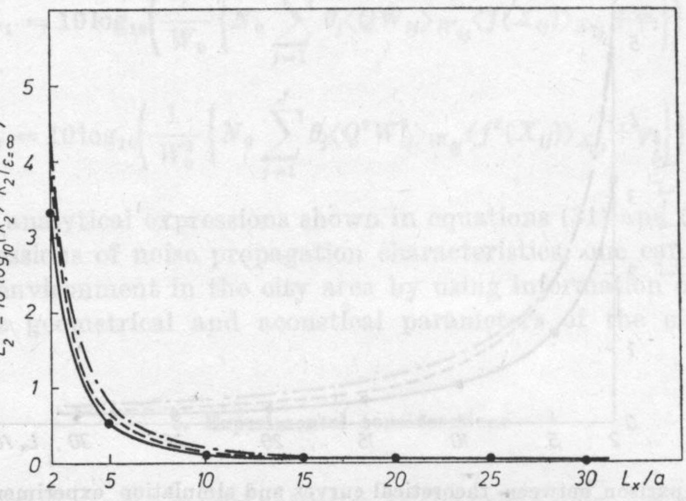

Fig. 7. A comparison between theoretical curves and simulation experiments with respect to L_2, in the case of $R(\xi) = 0.61$. The experimentally sampled points are marked by $\cdot$, and the theoretically predicted curves are respectively shown as —— (result by use of $f_0(x)$); — — — — — (result by use of $f_1(x)$); —— — —— (result by use of $f_2(x)$)

Fig. 5 shows a comparison between the experimental points sampled by the digital simulation technique and three different theoretical curves for L_1, calculated by using the most precise expression of the propagation characteristics, equation (10), and other approximate expressions of them, equations (11) and (12). In Fig. 5, since the averaged value of reflection coefficients in the urban area is considered as about 0.6–0.7, supported by its empirical value, a value of $\varepsilon = 0.5$ was chosen, corresponding to this reflection coefficient, $R(\xi) = 0.61$. In the case when the surrounding buildings have relatively high absorptive surfaces of $R(\xi) = 0.37$, corresponding to $\varepsilon = 1.0$ in equation (8), the predicted results are shown in Fig. 6. Moreover, the predicted results for the evaluation index L_2 are shown in Figs. 7 and 8 with respect to $R(\xi) = 0.61$ and $R(\xi) = 0.37$, respectively. From these figures, it is reasonable to say that the values predicted by use of the most precise expression $f_0(x)$ of the noise

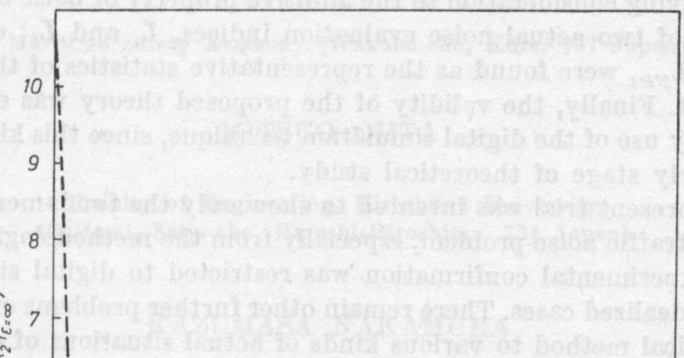

Fig. 8. A comparison between theoretical curves and simulation experiments with respect to L_2, in the case of $R(\xi) = 0.37$. The experimentally sampled points are marked by $\cdot$, and the theoretically predicted curves are respectively shown as —— (result by use of $f_0(x)$); — — — — — (result by use of $f_1(x)$); —— – —— (result by use of $f_2(x)$)

propagation characteristics were always in good agreement with the experimentally sampled points. Furthermore, if the approximate expressions $f_1(x)$ and $f_2(x)$ for practical use are suitably used, according to the actual situation of building surfaces, these expressions show good performance in evaluating the noise propagation characteristics in the city area.

5. Conclusion

In this paper, a fundamental prediction theory of the environmental noise in the city area was derived by use of the image method approach. That is, by using two factors of the spatial attenuation of noise waves and the acoustical absorption property of building surfaces, analytical expressions of the noise propagation characteristics for the typical urban noise environment were derived Next, giving consideration to the additive property of noise energy, unified expressions of two actual noise evaluation indices, L_1 and L_2, closely related to L_{eq} and L_{NP}, were found as the representative statistics of the street noise environment. Finally, the validity of the proposed theory was experimentally confirmed by use of the digital simulation technique, since this kind of research is at an early stage of theoretical study.

As this present trial was intented to show only the fundamental treatment of the road traffic noise problem, especially from the methodological viewpoint, then our experimental confirmation was restricted to digital simulation only for several idealized cases. There remain other further problems of how to apply this theoretical method to various kinds of actual situations of environmental noise in the city area.

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References

[1] H. KUTTRUFF, *Zur Berechnung von Pegelmittelwerten und Schwankungsgrössen bei Strassenlärm*, Acustica, **32**, 2, 57–69 (1975).

[2] D. W. ROBINSON, *Towards a unified system to noise assessment*, J. of Sound Vib., 14, 279–298 (1971).

[3] W. FELLER, *An introduction to probability theory and its application*, John Wiley and Sons, New York, 1957.

[4] M. OHTA, S. YAMAGUCHI, S. HIROMITSU, *Polyfrequency spectral analysis for the road traffic noise based on the filtered Poisson process model*, Proc. 4th Metting of I.F.A.C. on Environmental Systems, Planning, Design and Control, Report No. B6.1, 447–484 (1977).

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