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A simple model for estimating excess attenuation of road traffic noise

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Sound propagation over ground from a point source having a typical spectrum of motor vehicle noise was investigated by a computational study using theoretical models. Employing new parameters of an average propagation height and a classified resistivity of ground surface, a practical expression to estimate A-weighted excess attenuation was obtained with some charts for various source and receiver locations. Results of field and scale model experiment show a good agreement with the values estimated from this practical model. It is applicable to predict the sound levels of road traffic noise propagating over the ground with a typical acoustic impedance.

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1. INTRODUCTION

A practical procedure to predict road traffic noise was proposed by the technical committee of the Acoustical Society of Japan, in 1975.[1] The prediction formula of L_{50} was based on a model in which all vehicles were assumed to be radiating the same sound power and moving at a constant speed with equal spacings between them. Since the formula was very simple and easy to compute, the prediction procedure has been widely applied to planning and noise control of public road. This prediction method, however, was limited to freely flowing traffic and to relatively simple situations.

Recently, the committee has developed a computer simulation method[2] to extend the prediction procedure for as many situations as possible, especially for the prediction around an interchange of highway where the traffic is non-free flow and the sound propagation is relatively more complicated. In deriving the computer simulation method, existing materials published from many organizations have been taken into account and some additional studies have been made in order to supplement the data available to the simulation method. This paper describes one of the additional studies concerning the attenuation of noise from a single vehicle over various types of ground.

In developing a computer simulation method, one of the most important factors required for the simulation model is the attenuation of noise from individual vehicles, when propagating over ground. Several studies have been made for this purpose.[3-5] Among these studies, an empirical model for the attenuation of noise due to ground effect was reported by Nelson.[3] His model was established by several experiments on sound propagation over absorbent surfaces. Since the expression is presented in a form of A-weighted sound reduction per doubling of distance, it is easy to calculate, but this procedure is not available for various heights of a microphone and a noise source. Furthermore the type of ground specified in his paper can not be applied directly to the different types of ground under consideration.

On the other hand, well-established theories for sound propagation from a point source over an impedance boundary were used to estimate ground effect for highway noise.[4,5] The theoretical models are available for any location of source and receiver and for an arbitrary acoustical impedance of ground surface. But numerical computation is rather time-consuming, because some complicated functions unique to the theoretical models have to be computed for individual frequency components over a wide range.

In this paper a simple and practical model which provides A-weighted excess attenuation is described. After qualitative study of A-weighted excess attenuation, a new simple expression is proposed with some charts for various locations of the sound source and the receiver. Then, sound levels computed from this model are compared with the experimental results and the application of this model is discussed. In addition, some available data on ground resistivity derived from an empirical impedance model are introduced, which specifies the surface impedance of ground.

2. MODEL USED FOR COMPUTATION

2.1 Sound Field

So far, theoretical treatments of the sound field from a point source over an impedance boundary have been developed by many authors.[6-8] The theoretical model used in our work is based on the asymptotic solution that was formulated by Thomasson.[7] The total sound field above an impedance boundary (see Fig. 1) is given by

$$P=e^{ik_0R_1}/(-4\pi R_1)+e^{ik_0R_2}/(-4\pi R_2)+PR+PS, \quad (1)$$

where k_0 is the wavenumber. PR and PS are the corrections for the finite impedance of the boundary. They are expressed in terms of error function, Hankel function and related functions (see Ref. 7)). This theoretical model was programmed for a minicomputer, then sound levels calculated in a case where the sound source and the receiver were located close to the boundary were compared with the results obtained from an exact solution (see Ref. 9)). The deviation between the two results never exceeded 0.2 dB.

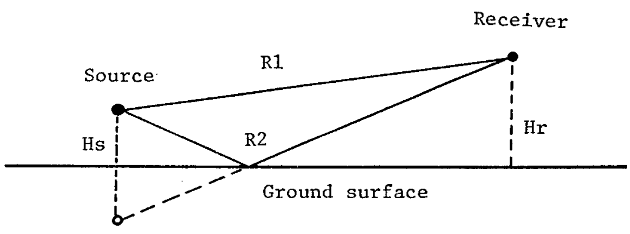


Fig. 1 The geometry of the source, the receiver and the ground surface.

The excess attenuation from the point source is defined by

$$\text{Excess Attenuation}=-20\log\left(\frac{\text{total field}}{\text{direct field}}\right) \quad (2)$$

which represents the attenuation in excess of that due to spherical spreading. In this paper, A-weighted excess attenuation is defined as excess attenuation on A-weighted sound pressure level.

2.2 Impedance Model

For the surface impedance of ground, Chessell[10] suggested the use of the empirical formula which Delany and Bazley.[11] originally proposed as a result of their acoustic measurement made on fibrous absorbent materials. This impedance model seems very convenient to our work because it is specified by only a single parameter, the flow resistance per unit thickness σ, which can be easily determined by a simple measurement of sound propagation over ground.

Miki,[12] however, corrected the Delany's formula and proposed a new formula based on Delany's experimental results. He obtained the positive real property after his precise measurements on acoustic impedance by an impulse response method. His impedance model is written by

$$\left.\begin{aligned}\mathrm{Re}(f)&=1+5.5(f/\sigma)^{-0.63},\\ \mathrm{Im}(f)&=-8.37(f/\sigma)^{-0.63},\end{aligned}\right\} \quad (3)$$

where $\mathrm{Re}(f)$ and $\mathrm{Im}(f)$ are the real part and the imaginary part of the normalized specific impedance respectively, and f is the frequency. He pointed out that the difference from the original one appeared in the case of a double layered medium whose impedance was expressed with a propagation constant.

The Miki model is used in our work in order to make a precise study of sound propagation by means of a scale model experiment where the ground surface is simulated by layered materials.

2.3 Measured Values of Ground Flow Resistance

To compute the sound field from Eqs. (1) and (3), we need to know the values of flow resistance for various types of ground. Several data are reported by Isei.[13] But they can not be applied directly to our work, because it was difficult to find a certain relation between his data and various types of actual ground such as a rice field and a vegetable field commonly seen at highway side.

Several measurements were carried out over these

Table 1 Type of ground vs. flow resistance σ evaluated from Miki model.

Type of ground	Condition	Flow resistance (Miki model)
	newly plowed	$50\sim75$ cgs units
Rice field	crops were reaped	$150\sim300$
	covered with rice plant (0.8 m heigh)	$600\sim1{,}250$
Vegetable field	flat and soft	$50\sim150$
Asphalt		more than 20,000
Lawn		150

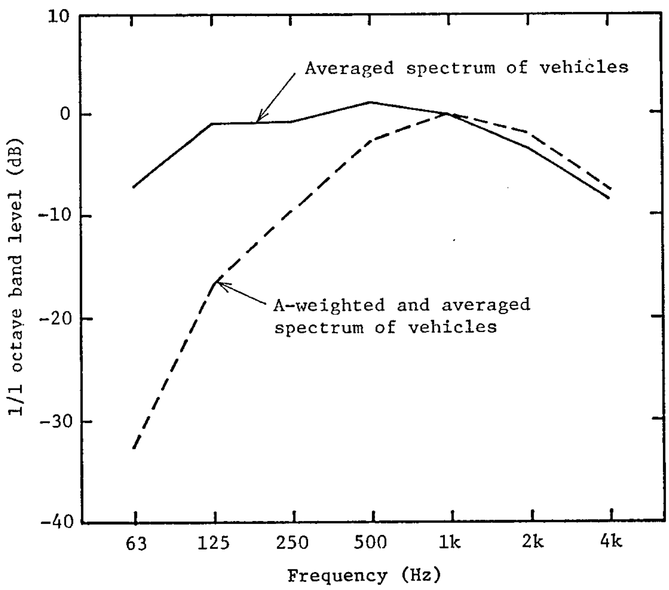


Fig. 2 Typical 1/1 octave band spectrum (from Ref. 14)) of vehicles and A-weighted spectrum used to estimate the A-weighted excess attenuation.

surfaces at short ranges. The measured data were compared with the excess attenuation calculated from Eqs. (1), (2) and (3), then the parameter σ was adjusted to obtain the best fit between them. The results are shown in Table 1. The results obtained from lawn and asphalt surfaces are also included.

The rice field is considered to be acoustically variable field, for the ground is filled with water in summer, abundant in crops of rice in fall, and newly plowed out in winter. Thus it seems to provide both the hardest and the softest surfaces acoustically in a year. As shown in Table 1, the flow resistance of rice field is ranged from $50\sim75$ cgs units for the newly plowed surface, through $150\sim300$ cgs units for the surface after the crops have been reaped and up to $600\sim1{,}250$ cgs units for the surface covered with rice plants (0.8 m height). Furthermore it is supposed that the value of σ is more than 20,000 cgs units for the field filled with water.

But it should be noted that in the case of a field with surface irregularities, considerable scatter appeared in the excess attenuation vs. frequency characteristics. This situation makes it difficult to determine the value of σ, and such data are excluded here.

2.4 Spectrum of Vehicle Noise

The noise from a single vehicle moving at a constant speed consists of engine noise, tire noise, exhaust noise and aerodynamic noise. The spectrum of vehicle noise is therefore dependent on types of individual vehicles and their moving speed. Tachibana *et al.*[14] reported the spectra of vehicle noise together with the sound power levels measured in a reverberant field of a road tunnel. The spectra were classified to two types of vehicles, i.e., heavy trucks and passenger cars. In order to simplify the prediction procedure, the averaged and A-weighted spectra of these data were used in our work as typical spectra of the vehicle noise, which are shown in Fig. 2.

3. A-WEIGHTED EXCESS ATTENUATION

In order to make qualitative studies of the noise propagation from a vehicle, the sound level of each frequency component (A-weighted) was calculated by means of Eqs. (1) and (3). These results are plotted in Fig. 3 as a function of the horizontal distance from the source, in the frequency range 125 Hz$\sim$2 kHz (center frequency of the octave band) and they are compared with each other. The sound source was assumed to be at a height of 0.3 m above the surface, the receiver at 1.2 m height and the flow resistance of the ground surface 300 cgs units.

Figure 3 shows that the lowest octave band frequency of 125 Hz is predominant over the distance of 100 m. On the contrary, the octave band frequency of 1 kHz, which is the predominant component of the typical A-weighted vehicle noise (see Fig. 2), shows the lowest value in the same range. This is obviously owing to the different rate of sound attenuation with the distance. Namely, the sound level of 1 kHz decreases with a rate of 12 dB per doubling of distance beyond 100 m, but that of 125 Hz remains at a rate of 6 dB per doubling of distance

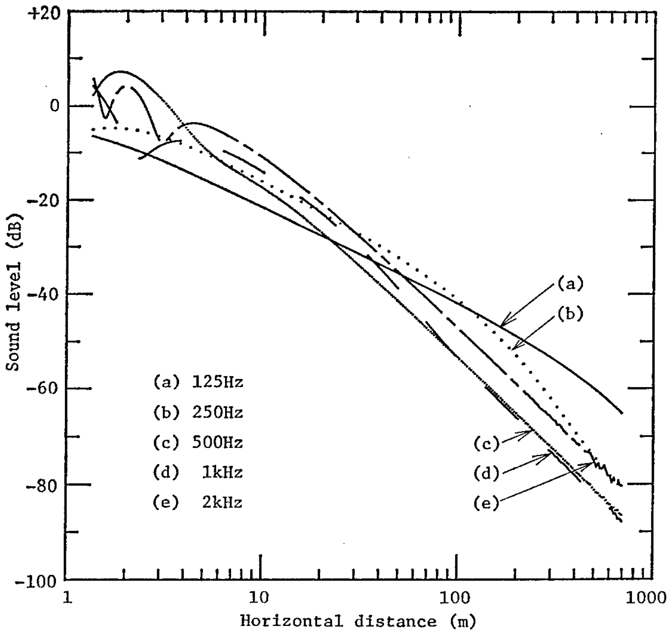


Fig. 3 Comparison of sound levels calculated for octave band frequency components of A-weighted vehicle noise. The source and receiver heights are 0.3 m and 1.2 m above the ground respectively, and the ground resistivity is 300 cgs units.

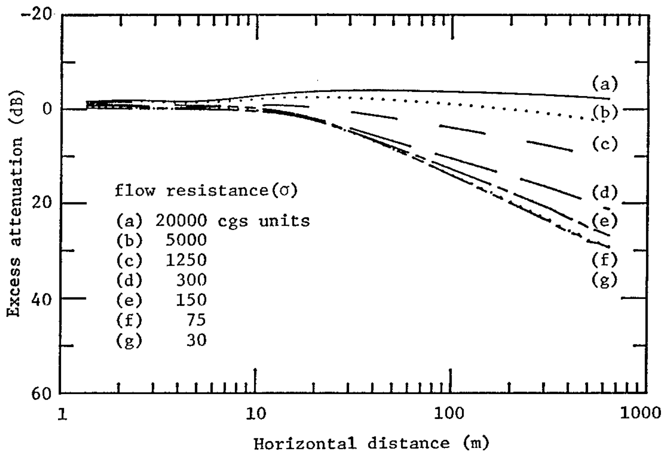


Fig. 4 Comparison of A-weighted excess attenuation for various values of the surface flow resistance. The source and receiver heights are 0.3 m and 1.2 m respectively.

up to more than 200 m. It is suggested that the predominant component of vehicle noise is shifted to lower frequencies at a long distance, when propagating over an absorptive surface.

Next, A-weighted excess attenuation was computed from Eqs. (1), (2) and (3), for various values of parameter σ in the range from 30 cgs units to 20,000 cgs units. The results were obtained by integrating sound components over the frequency range 50 Hz $\sim$ 5,000 Hz (1/12 octave band) for the typical spectrum of A-weighted vehicle noise and they are shown in Fig. 4. The source and the receiver heights are 0.3 m and 1.2 m respectively.

Figure 4 shows that the A-weighted excess attenuation over each surface appears between 0 dB and -3 dB within the range of 10 m from the source. But beyond the range of 10 m, the A-weighted excess attenuation increases remarkably with the distance especially for the surface flow resistance below 1,250 cgs units.

We can see that the rate of increase in the excess attenuation becomes 6 dB per doubling of distance in maximum. Moreover it is suggested that the A-weighted excess attenuation can be expressed approximately as a straight line at a long distance and its increasing rate is dependent on the ground flow resistance.

4. A SIMPLE MODEL FOR THE ESTIMATION OF A-WEIGHTED EXCESS ATTENUATION

Next, let us try to establish a simple and practical formula for the estimation of A-weighted excess attenuation. Assuming that the A-weighted excess attenuation increases proportionally to the common logarithm of the distance, the formula will be basically written by $K\log_{10}r$, where r is the distance from the source and K is a constant. It can be also expressed as $K\log_{10}(r/r_0)$ by setting a specific distance of r_0. At a distance within r_0, the excess attenuation is assumed to be a constant value of -3 dB, then the formula is expressed by

$$E.A.=\begin{cases} K\log_{10}(r/r_0)-3\,, & \text{for } r>r_0\,, \\ -3\,, & \text{for } r<r_0\,, \end{cases} \tag{4}$$

where $E.A.$ stands for A-weighted excess attenuation.

In order to calculate the A-weighted excess attenuation by means of Eq. (4), the values of K and r_0 have to be determined. These values are related to the heights of the source (H_s) and the receiver (H_r), the distance between them (r) and the flow resistance of the ground surface (σ). The problem which has made our work hard and troublesome is that the factors are too many in number to determine the values of K and r_0. To avoid this problem a new parameter of $H_a=(H_s+H_r)/2$, the mean prop-

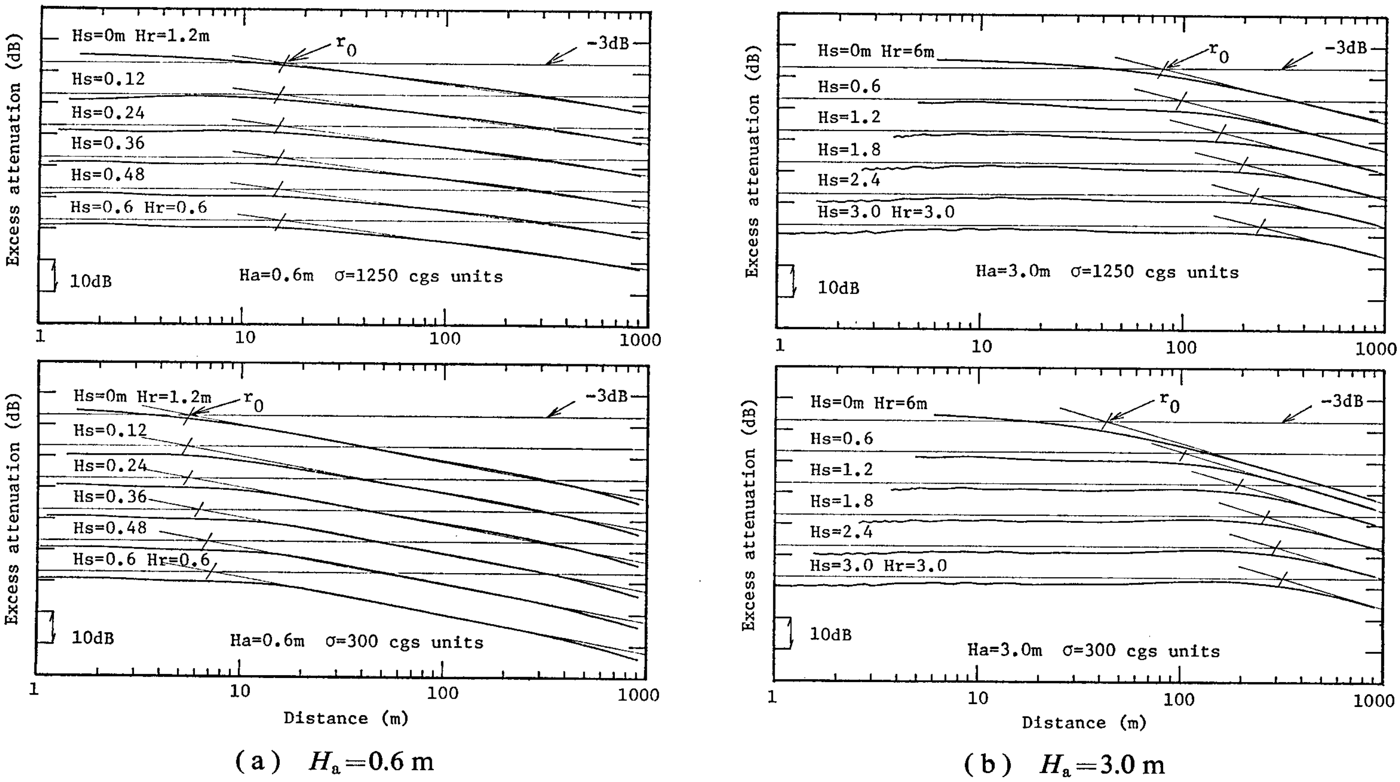


Fig. 5 A-weighted excess attenuation calculated under the condition of the same mean propagation height, i.e., H_a, for three cases of σ=1,250 cgs units and σ=300 cgs units. The slant straight lines are the most suitable to each calculated values in the range from 10 m to 1,000 m. The locations of r_0 are the cross points between the excess attenuation of −3 dB and these lines.

agation height, is introduced.

Under the condition of the same mean propagation height, A-weighted excess attenuation was computed for different values of H_s and H_r. The results are shown in Fig. 5 for the mean propagation heights of 0.6 m and 3.0 m respectively. They also include both the cases of the flow resistance, 300 cgs units and 1,250 cgs units. In Fig. 5, the best fitting lines to the theoretical A-weighted excess attenuation are drawn and the locations of r_0 are marked. These results show that the rate of increase in the excess attenuation is approximately constant under the condition of the same mean propagation height. Strictly speaking, each A-weighted excess attenuation in these figures doesn't show exactly a straight line, but it seems very useful to treat them as the lines having the same rate of increase in determining the values of K and r_0.

On the other hand, the location of r_0 is dependent on the relation of H_s and H_r in H_a, which is clearly seen in Fig. 5 (b). The location of r_0 is shifted to the source when either the source or the receiver is located close to the ground surface.

5. CHARTS

On the basis of the qualitative description in the previous chapter, it will be convenient to draw up charts for determining the values of K and r_0, and the following relations are assumed:

(1) The parameter K is expressed as a function of the mean propagation height.
(2) The parameter of r_0 is expressed as a function of the smaller value of H_s or H_r.
(3) Both K and r_0 are dependent on the ground flow resistance.

To establish the chart which describes the relationship between K and H_a, A-weighted excess attenuation was computed for various mean propagation heights in the range 0.6～6.0 m, and the ratio of H_s and H_r was changed in six values. The value K was determined as the best fitting gradient of the increasing *E.A.* vs. the distance within the range 10～1,000 m.

Figure 6 shows the relationship between the best

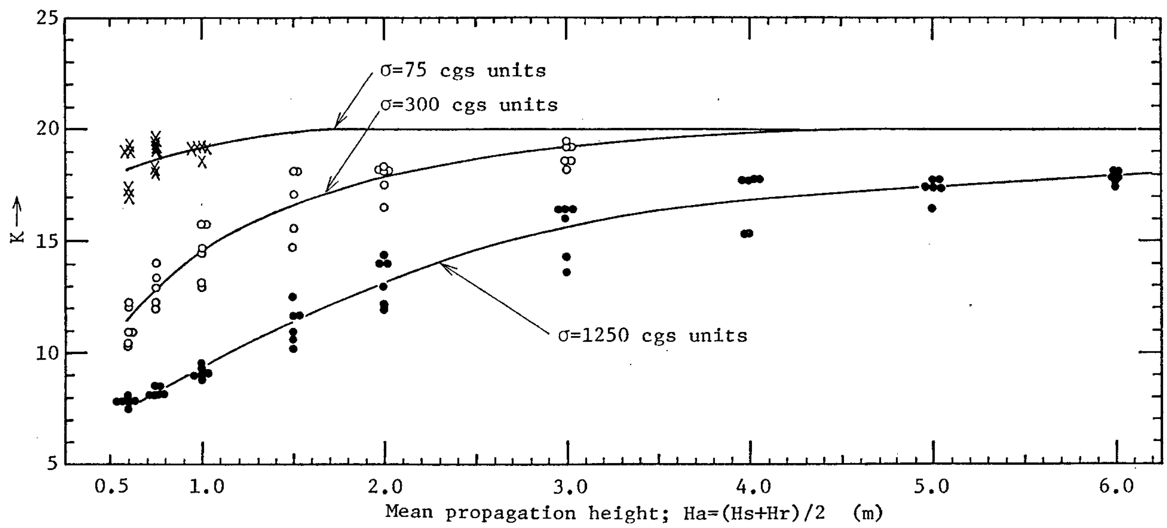


Fig. 6 The relationship between K and mean propagation height for three types of ground, i.e., $\sigma=75$ cgs units, $\sigma=300$ cgs units and $\sigma=1{,}250$ cgs units.

fitting value of K and the mean propagation height for three types of ground surface, i.e., 75 cgs units, 300 cgs units and 1,250 cgs units. The smooth lines were also drawn through the mean values of K.

The values of K are ranged from 8 to 20 and increase with the mean propagation height. One may have an impression that the large value of K causes a large amount of the excess attenuation when the location of both the source and the receiver are far from the ground surface. But, as is shown next, the value of r_0 provides the balance between the large value of K and the total amount of the excess attenuation.

The values of r_0 are determined from the intersection of -3 dB line and the extension of the best fitting straight line to the theoretically computed A-weighted excess attenuation. The gradient of the straight line is referred from the smooth line shown in Fig. 6. The results are plotted in Fig. 7 for various values of H_a as a function of the smaller value of H_s or H_r. The results show that the value of r_0 becomes small when either the source or the receiver is located close to the ground surface and increases as the mean propagation height increases.

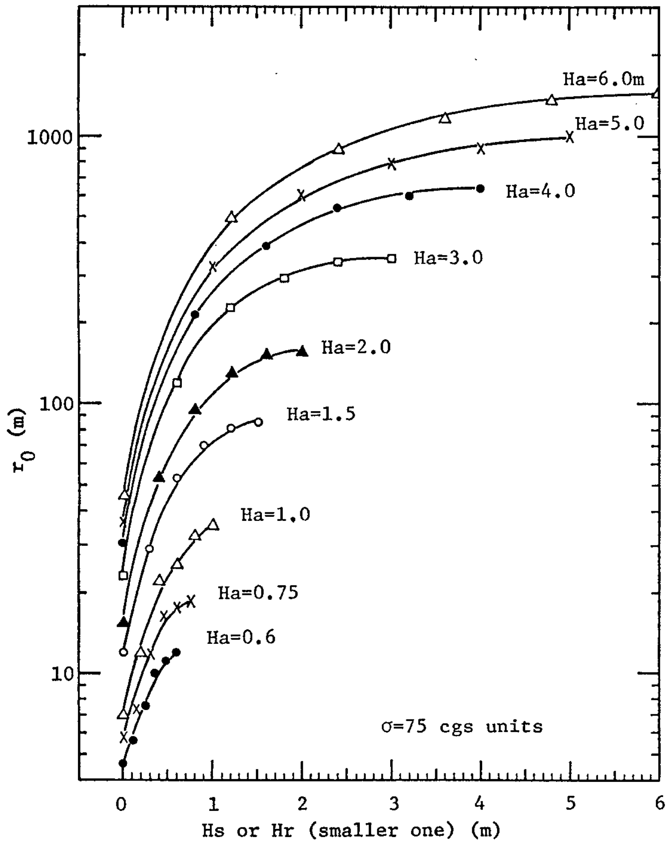
In this way we can estimate the A-weighted excess attenuation of vehicle noise by means of Eq. (4) and the charts in Figs. 6 and 7.

6. APPLICATION AND DISCUSSION

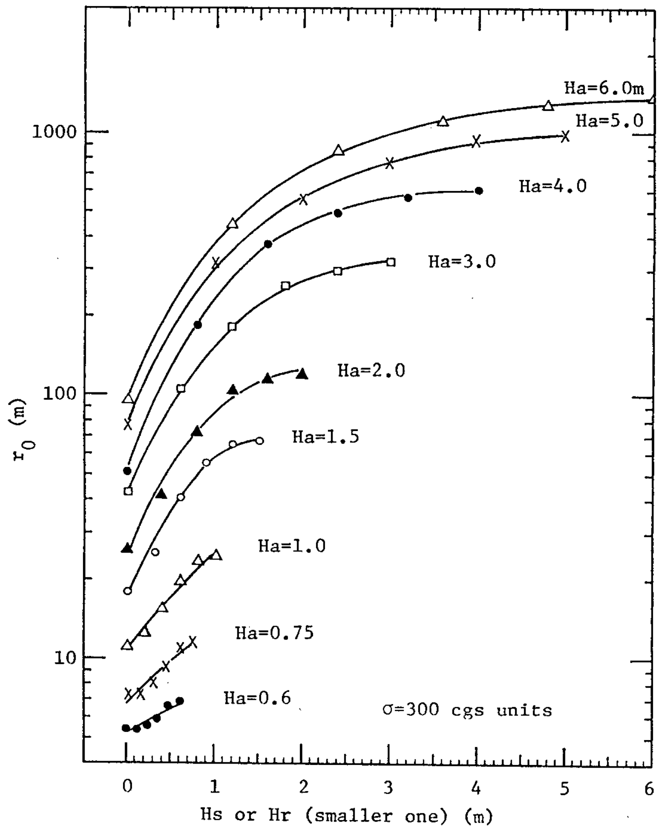
6.1 Comparison with Field Data

Sound levels at the receiving point were calculated from Eq. (4) by the aid of charts and geometrical spreading, and compared with the data obtained from field measurements made on rice fields. Figure 8 shows the results for three different ground surfaces, i.e., (1) the rice field with short rice plants of about 0.8 m height, (2) the same field just after the crops were reaped and (3) the field newly plowed. For the experimental data, each frequency component (octave band) of the sound source (loud speaker) were adjusted to fit the spectrum of A-weighted vehicle noise, therefore they represent the over all A-weighted sound level from a single vehicle. For each field data, three calculated lines are presented. These are respectively: (1) for $\sigma=1{,}250$ cgs units; (2) for $\sigma=300$ cgs units; and (3) for $\sigma=75$ cgs units. Both the calculated data and the experimental data are plotted relative to those of 2 m point from the sound source as references.

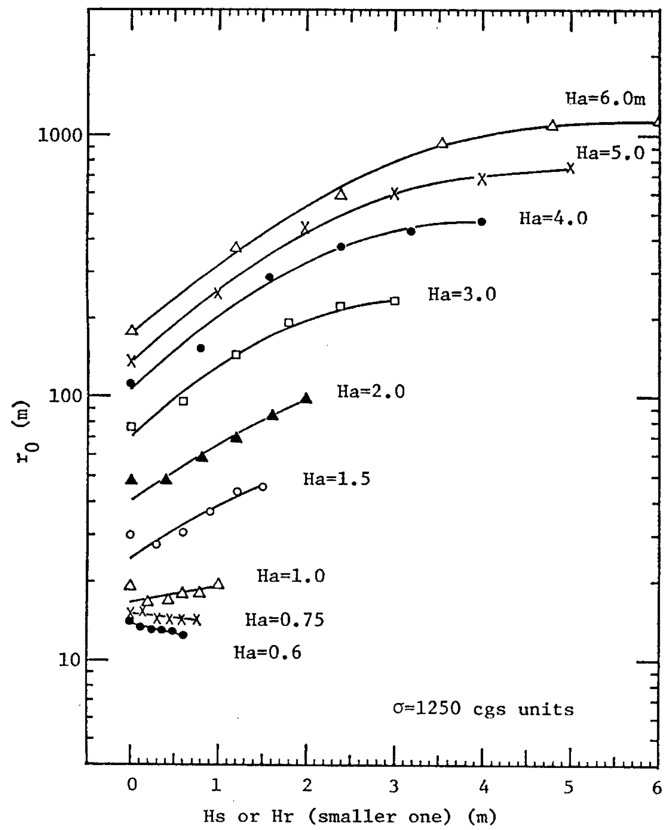
Figure 8 (a) shows the results for the case where the sound source and the receiver are both located at a height of 1.2 m above the ground. One can see that each calculated line consists of two straight lines of different gradient. Clearly, the line at short distances represents only the geometrical spreading and the line at long distances represents the geometrical spreading plus the excess attenuation due to the ground effect. To compare these lines with the experimental data, there is reasonably a good qualitative agreement in all three cases, though one may note the considerable deviations of the experimental data for the case of newly plowed field at long distances. These deviations are considered to be due to the unexpected change in meteorological condition



(a) $\sigma=75$ cgs units



(b) $\sigma=300$ cgs units



(c) $\sigma=1{,}250$ cgs units

Fig. 7 The relationship between r_0 and the smaller value of H_s or H_r.

during the measurement, because all the field measurements has been carried out under calm weather conditions with vector wind less than ± 1.0 m/s.

Figure 8 (b) shows the similar comparison for the receiver height of 3.5 m. In this case, the excess attenuation appears at the longer distances than the case of Fig. 8 (a).

6.2 Comparison with Data from Scale Model Experiment

Field data measured at long distances are often affected by the meteorological condition during the measurement, therefore the quantitative discussion of the ground effect for these data seems to be rather difficult. In order to make quantitative comparison between experimental data and calculated ones precisely, a scale model experiment was carried out, where the meteorological factors could be negligible.

In this case, the sound levels are calculated by,

$$SL = PWL - 20\log_{10} r - 11 - E.A. \qquad (5)$$

where SL and PWL represent A-weighted sound level and A-weighted power level of the sound source respectively. The value of $E.A.$ is calculated from

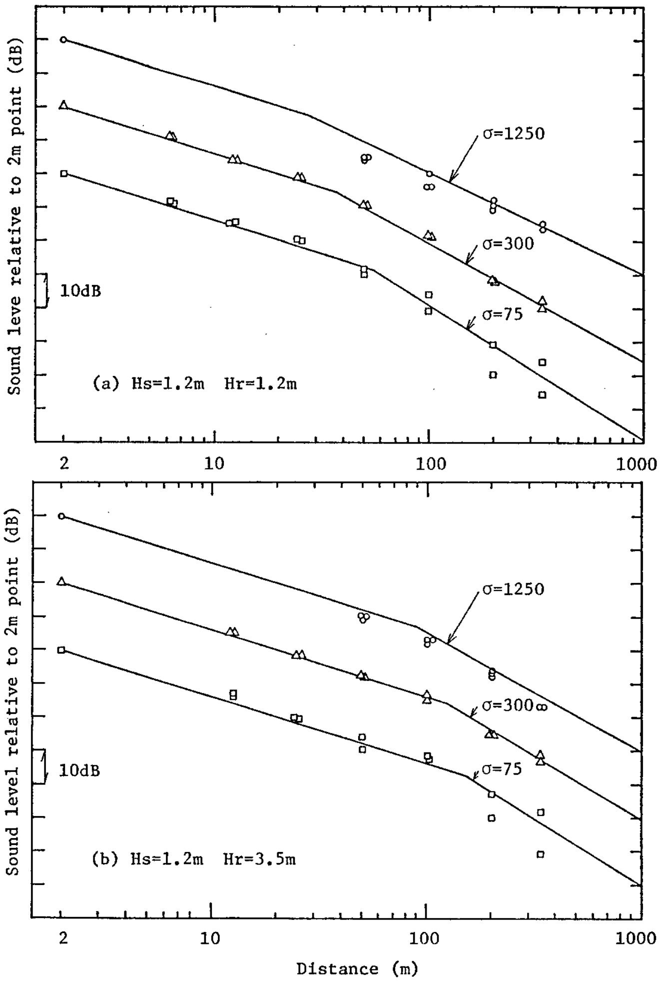


Fig. 8 Comparison between the calculated values and the sound levels measured at three different conditions of ground surface, i.e., points ○ are at a rice field covered with short rice plants of 0.8 m height, △ at the same field just after the crops were reaped and □ at the field newly plowed. The source and receiver heights are respectively: (a) $H_s=1.2$ m, $H_r=1.2$ m; (b) $H_s=1.2$ m, $H_r=3.5$ m.

Eq. (4) and the related chart.

For the scale model experiment (scale factor 1/50), the surface resistivity of $\sigma=300$ cgs units (by Miki model) was chosen as a typical ground surface. After several model experiments on sound propagation over model surfaces in a short range, cotton sheet of 0.5 mm thickness was selected as the surface material, which was attached to the floor surface (concrete) in a semi-anechoic room. Over this model surface, sound propagation from a point source was measured and A-weighted sound levels were obtained after adjusting the spectrum of the sound source (jet noise type) to that of vehicle noise.

Figure 9 (a) shows a comparison between the sound level from the scale model experiment and the calculated value obtained from Eqs. (4), (5) and the related chart. The source height was assumed to be 0.3 m above the ground and the receiver height 1.2 m, and the A-weighted sound power level of the sound source was 100 dB. A good quantitative agreement was obtained over the distance of 20 m from the source. The overestimate in sound level appeared at the distance of 10 m, which was considered to be due to the approximation error between the theoretical curve and the simple straight line.

Figures 9 (b) ~ (d) show the similar comparisons for three receiver heights, i.e., $H_r=1.2$ m, $H_r=3.5$ m and $H_r=7.0$ m, but in these cases the sound source of the scale model is located above a hard ground surface of $\sigma=20{,}000$ cgs units which is the typical value of a road surface. It should be noted that this situation is theoretically treated as the problem of ground with an impedance discontinuity.

The values calculated from our simple model show a little underestimate to the experimental results. But the sound levels obtained from the experiment can be approximately expressed by the simple model described above.

7. CONCLUDING REMARKS

The comparisons described in the previous sections show the applicability of the estimation for the A-weighted excess attenuation by Eq. (4) and the charts as shown in Figs. 6 and 7. But as is shown in Table 1, ground surfaces show various values of flow resistance even on a same field, furthermore the actual ground has its surface irregularities, which cause deviations in excess attenuation. Therefore it is recommended that the type of ground is classified to several categories in the actual prediction stage. In this case one may rebuild the charts by changing the ground resistivity in computational study in a theoretical model, or one may establish similar charts by some careful outdoor measurements.

As for the spectrum of vehicle noise employed in our work, it gives the mean value of A-weighted excess attenuation to compare with the spectra of heavy trucks and passenger cars reported in Ref. 14). The maximum deviation between them was ±1.5 dB at a distance of 1,000 m from the source. The height of the source and the receiver were 0.3 m and

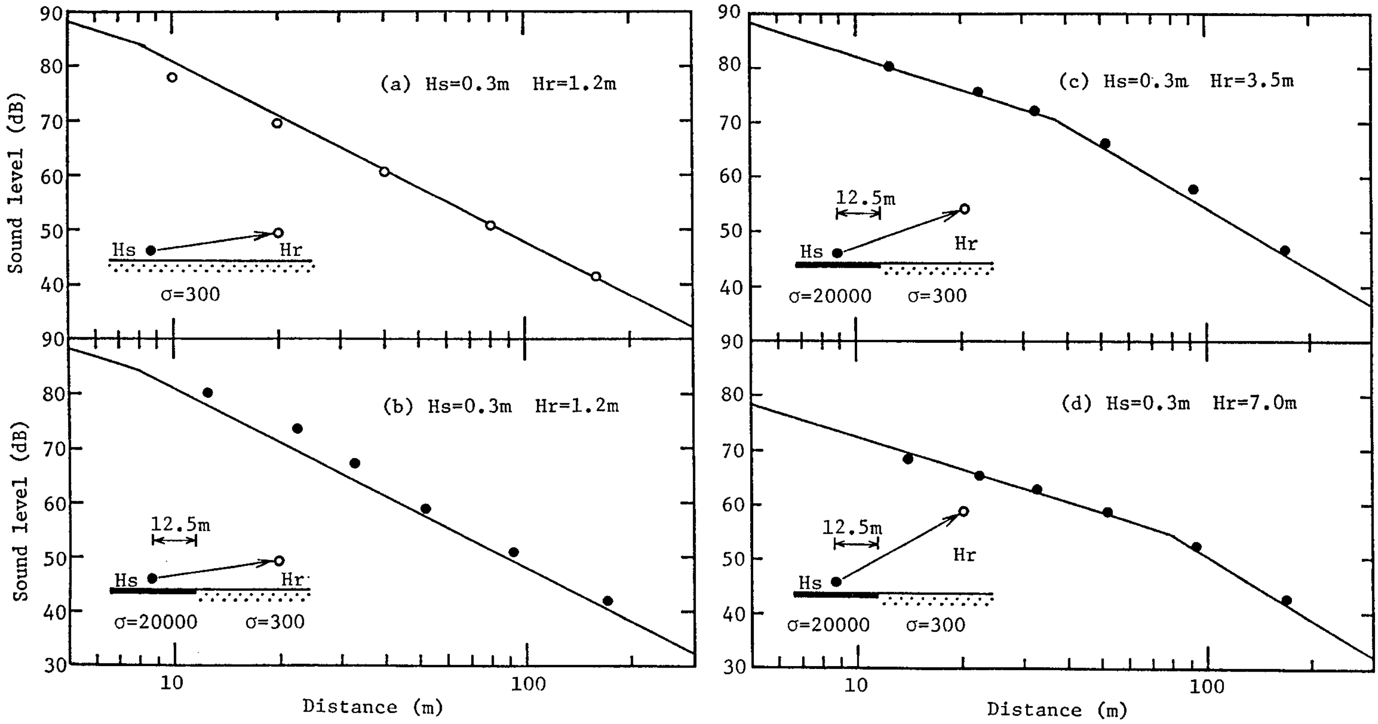


Fig. 9 Comparison between the calculated values from Eq. (5) and the sound levels obtained from the model experiment. The source and receiver height, and the surface resistivity are respectively: (a) H_s=0.3 m, H_r=1.2 m, σ=300 cgs units; (b) H_s=0.3 m, H_r=1.2 m, σ=20,000 cgs units for the portion of hard ground (beneath the source), σ=300 cgs units for the portion of soft ground; (c) the same plots as (b) except for H_r =3.5 m; (d) the same plots as (b) except for H_r=7.0 m.

1.2 m respectively and the flow resistance was 1,250 cgs units. Therefore, in most cases the typical spectrum of vehicle noise shown in Fig. 2 will give the reasonable results. On the other hand, the spectra of vehicle noise will be different in such a case as stop and go traffic where the vehicles are accelerating. In this case another chart may be needed, and the most reliable data of spectra have to be gathered.

For the prediction of road traffic noise by a computer simulation, the time history of sound levels from a single vehicle can be estimated from Eq. (5) and the additional diffraction effect by barriers should be considered in a special case. But it is necessary to take into account a coupling between the ground effect and the diffraction effect, because the former can be replaced by the latter when the barrier is erected on an absorptive ground. Furthermore the problem of ground with impedance discontinuity must be reasonably solved as well when applying the above simple expression to the prediction procedure.

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