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by

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INTRODUCTION

In 1977 the Canada Mortgage and Housing Corporation (CMHC), with the technical assistance of the Division of Building Research, produced the publication "Road and Rail Noise: Effects on Housing". That paper presented procedures for predicting the noise from road and railway traffic, and specified acoustical requirements for residential buildings in their vicinity. The procedures were simplified to the point where they can be handled by persons with limited mathematical training and no knowledge of acoustics. The objective of this present paper is to describe the underlying acoustical principles and explain how they relate to the procedures given in the CMHC document. The paper is divided into nine sections, roughly paralleling the steps in the CMHC document.

1. NOISE EMITTED BY ROAD TRAFFIC

The main factors that govern noise generated by freely-flowing road traffic include the number of vehicles passing per unit time, traffic speed, the fraction of heavy vehicles, and the type and condition of the road surface.

In formulating a noise prediction model, a reasonable starting point is the noise emitted by typical individual vehicles. For simplicity this model uses only two vehicle categories: "light vehicles" comprising passenger automobiles and similar four-wheel vehicles, and "heavy vehicles" defined as anything having more than four wheels. The relationship between the maximum passby noise emitted by light and heavy vehicles, as illustrated in Figure 1.1, was based on analysis of all available data from several sources.

The noise from light vehicle passbys has been the subject of numerous studies (1 to 5). All the data exhibit a steady increase in the maximum passby noise with increasing vehicle speed. In most cases an expression of the form a + b log (S) (where S is the traffic speed in kilometers per hour and a and b are regression coefficients) has been fitted to the data. There is some variation in the coefficients from one study to another, which may in large part be explained by differences in the road surfaces. Some tabulated results follow:

Study	Coefficient b
Rathe (dry asphalt) [1]	30
Rathe (dry concrete) [1]	33
Lewis (all sites) [3]	32.8
Ullriche (all sites) [4]	41.2

A median value of b = 35 was found to give a reasonably good fit to all available data sets and was adopted for this model.

The noise emitted by heavy vehicles has a more complicated dependence on vehicle speed. Studies of the passby noise from individual heavy vehicles (2,6) show that noise from the power train (engine, exhaust, etc.) tends to dominate at low speeds, but tire noise becomes increasingly significant at higher speeds and tends to dominate at speeds above 80 km/h. At speeds where tire noise dominates, the speed dependence of the noise emissions is very similar to that for light vehicles. At speeds below about 80 km/h, the noise depends primarily on engine speed and because drivers tend to shift gears often to maintain optimum engine speed, the noise is less dependent on vehicle speed. The final form of the curve for heavy vehicles in Figure 1.1 was obtained by a detailed comparison with actual field measurements.

For light vehicles, the assumed speed dependence of the maximum passby noise leads to an expression for the equivalent sound level near the road of the form:

$$L_{eq}(24\ h) = 25 \log(S) + 10 \log(N) - R \qquad [1.1]$$

where S is the speed in kilometres per hour, N is the number of light vehicles per 24 hours and R is a constant that depends primarily on the location of the point of reception and on the type of road surface. The variation in actual road surfaces will presumably be one source of scatter in the relationship between measured and predicted noise levels. Because at any specific site this feature may change appreciably due to aging and deliberate changes in surface, it seems reasonable to ignore it in a model used for long-term planning.

Equation 1.1 can be adapted for a traffic flow including heavy vehicles by treating each heavy vehicle as equivalent to t light vehicles. The value of t for any traffic speed is such that $10 \log_{10}(t)$ equals the difference between the maximum passby noise emitted by light and heavy vehicles at that speed, as shown in Figure 1.1. The values of t for common traffic speeds are presented in Table 1.1.

Table 1.1

Values of t for Common Traffic Speeds

Traffic Speed (km/h)	Appropriate Value of t
40	21
50	18
60	16
70	14
80 or greater	13

Using these values, the expression for the equivalent sound level 30 m from the road centreline may be expressed as:

$$L_{eq}(24\ h) = 25 \log(S) + 10 \log(N) + 10 \log[1 + x(t - 1)] - 26\ \text{dB} \qquad [1.2]$$

where x is the fraction of N that are heavy vehicles
t is the appropriate value from Table 1.1.

The value of R = 26 dB was obtained by fitting Eq 1.2 to actual traffic noise data, taking S to be the posted speed. The curves in Figure 1.2 present the levels predicted by Eq 1.2 for common posted traffic speeds. Note that these curves and the equation assume free-flowing traffic on a level road, and require further corrections in the presence of barriers or ground attenuation. These corrections are discussed in the following sections.

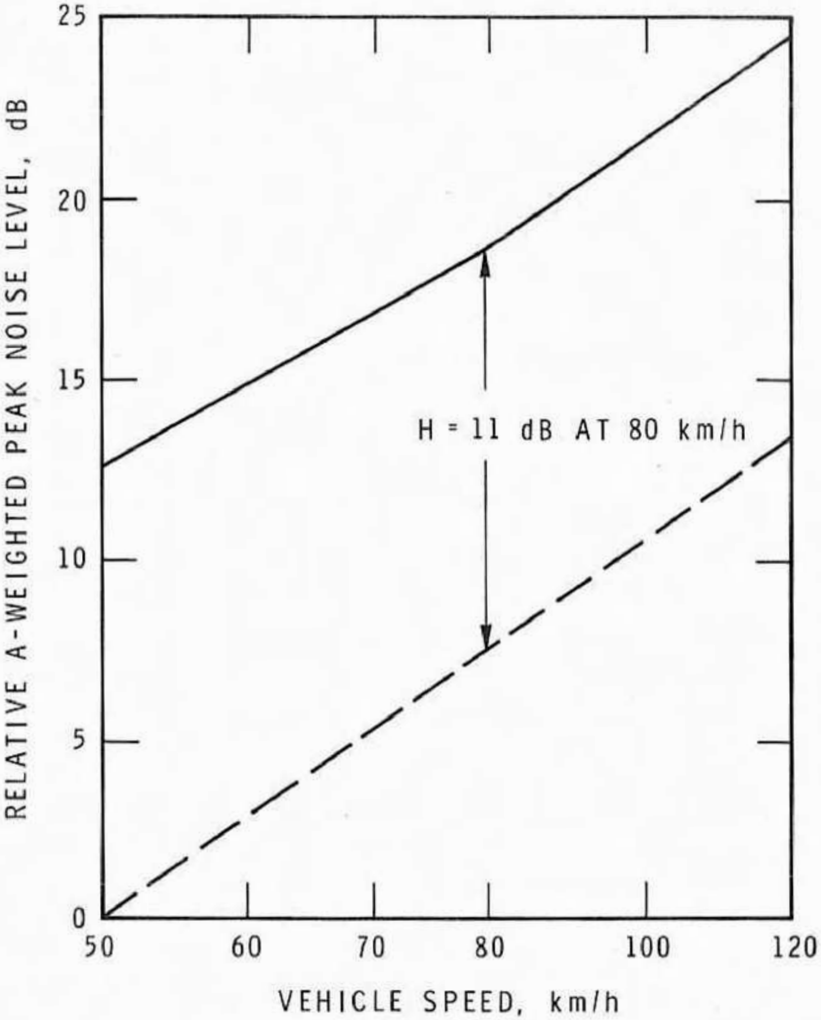

FIGURE 1.1

ASSUMED RELATIVE PEAK NOISE LEVELS FOR INDIVIDUAL VEHICLE PASS-BYS. THE SOLID LINE AND DASHED LINE REPRESENT THE PEAK LEVELS FOR HEAVY VEHICLES AND LIGHT VEHICLES, RESPECTIVELY

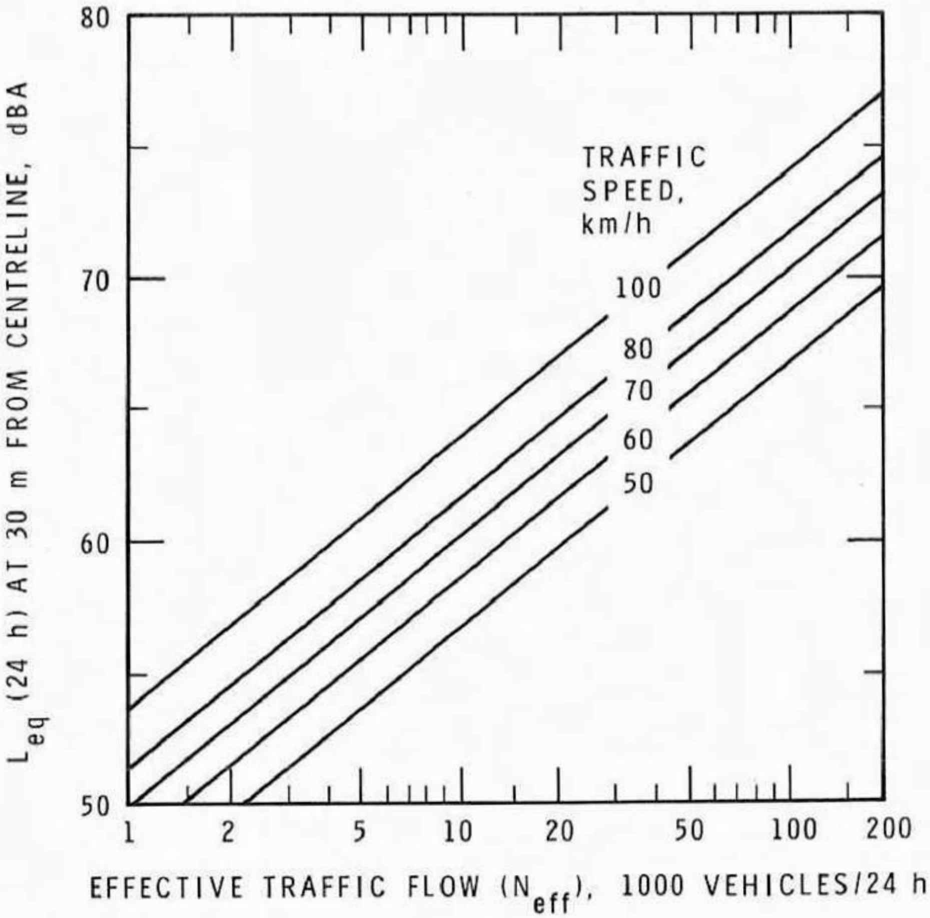

FIGURE 1.2

PREDICTED EQUIVALENT SOUND LEVEL (L_{eq} (24 h)) AT 30 m FROM CENTRELINE (BEFORE CORRECTIONS)

2. CORRECTION FOR ROAD GRADIENT

The effect of a road gradient on the noise emitted by traffic has been discussed in several studies (7 to 10). There is general agreement that noise emission from light vehicles is not appreciably affected by typical road gradients. With regard to heavy vehicles, most studies agree that there is some effect, but they differ appreciably in their conclusions as to the magnitude of the effect and its dependence on gradient. In part this may be ascribed to the different noise descriptors used in the various studies or to differences between the vehicle populations studied. The differences, however, may also be due to other parameters (such as the length of the incline) which have generally been ignored.

When analysed with respect to an individual vehicle, the problem is rather complicated. On an upgrade, the instantaneous engine and exhaust noise are increased because of the increased power requirement, but instantaneous tire noise is decreased if there is a reduction in vehicle speed. On a downgrade the converse is true. Because of the difference in passby duration, the noise from vehicles on the upgrade will contribute more of the total sound energy than would be inferred from the maximum passby sound levels alone. The balance between these effects for an actual road with traffic travelling in both directions depends on the characteristics of the heavy vehicles and on the speed profile of the passbys (which in turn depends on the posted speed limit and the length of the incline). The problem may be further complicated if the receiving point is near the end of the inclined section, or if the distances from the receiving point to the uphill and downhill lanes are appreciably different.

The correction to the equivalent sound level presented in Figure 2.1 is based on the approximate correction proposed in Ref. (10), which appears to be based on the most complete analysis of the relevant variables and falls in the mid range of the corrections proposed in the literature. Some extrapolation was necessary to extend the correction to situations where the percentage of heavy vehicles is less than 10 per cent, but the possible errors in this procedure are not likely to be significant.

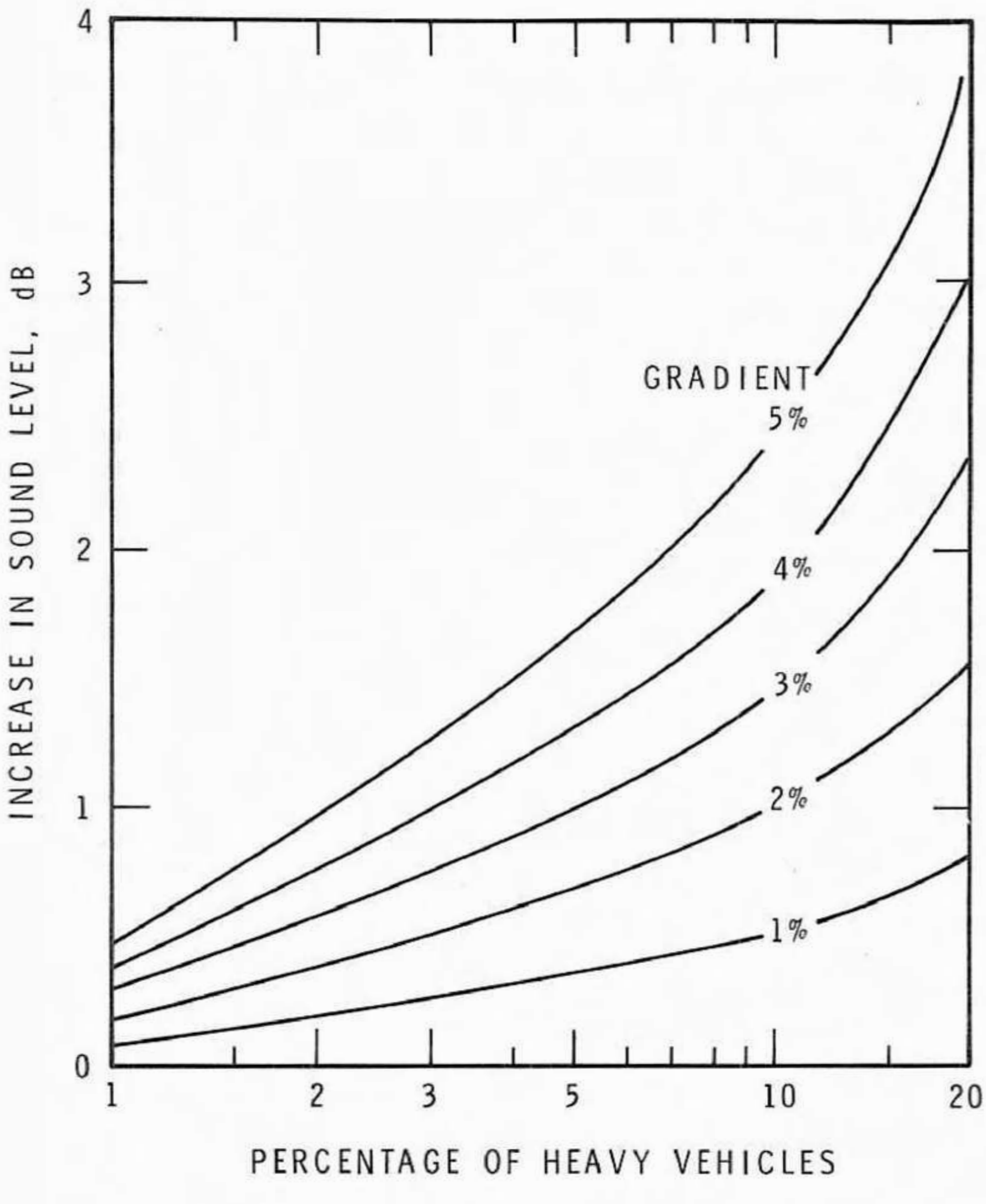

FIGURE 2.1

CORRECTION TO PREDICTED L_{eq} (24 h) TO ALLOW FOR ROAD GRADIENTS

3. NOISE SOURCE LOCATION

The preceding sections deal with the sound energy emitted by traffic. In order to predict how much of that sound energy reaches a receiver location, it is necessary to define the position of the source relative to the receiver. Because a multilane road with a mixture of light and heavy vehicles is a complicated distributed source, the rules formulated here for locating a nominal single source position involve some approximations. To keep the resulting errors within reasonable bounds, it is sometimes necessary to treat a road system as two or more separate sources, and to calculate the total sound level by combining the sound energy reaching the receiver from each source.

This model uses the basic rule that the nominal source position is midway between the outer edges of the paved road surface (i.e., at the centreline of the road). If the distance from the receiver position to the nearest edge of the pavement is less than half the distance to the nominal source position, the source should be divided into two or more sources each of which satisfies the above requirement. This procedure is illustrated in Figure 3.1 for the common case of a four-lane highway with a wide median strip. The traffic flow is assumed to be equally divided among the lanes.

The attentuation of noise when propagated over a distance (particularly if the path is interrupted by a barrier) depends on the height of the source relative to the ground and to the top of the barrier.

The primary sources of noise from automobiles and light trucks are the power train, the exhaust, and the interaction of the tires with the road surface. Exhaust outlets on light vehicles are usually situated about 0.3 m above the road surface. Noise from the tire-road interaction is generated very near the road surface, but reflections from the vehicle underbody and rattle from the undercarriage may also contribute. Taking all these factors into account, a source height of 0.3 m is considered appropriate for light vehicles.

For heavy vehicles, a larger fraction of the sound energy is attributed to engine compartment and exhaust noise, particularly at low speeds. At speeds below 30 km/h the noise emitted by such vehicles appears to be reasonably well represented by a single source located approximately 2.4 m above the road surface. Since engine speeds are generally held within close limits, the maximum passby noise from this source tends to be independent of speed (2,6). As in the case of light vehicles, the tire-road interaction produces a level that increases with increasing speed and is the dominant source at high speeds. Bearing in mind the contributions of the power train, undercarriage rattle, and reflections from the underbody, this source was assigned a height of 0.3 m.

Thus a line of traffic can be viewed as two line sources; one at 0.3 m and one at 2.4 m above the road surface with their relative strengths depending on the traffic speed and the fraction of heavy vehicles.

A calculation of the sound level at a receiving point would therefore require a separate calculation for each of the two sources, with the two calculated levels combined according to their energy to give the resultant level. To simplify this calculation, a single effective source height can be derived that, for any combination of traffic speed and mix, will give approximately the same resultant sound level as the combination of the two sources.

The fraction of the total sound energy generated by heavy vehicles can be determined from the expression

$$tx/[1 + (t - 1)x]$$

where x = fraction of heavy vehicles,
t = coefficient from Table 1.1 (p.)

for each speed and traffic mix. Assuming that at 110 km/h the noise emitted from heavy vehicles is dominated by tire noise (90 per cent of the total sound power) which decreases by 12 dB per halving of the speed,* and using Figure 1.1, the fraction of heavy vehicle noise emitted at a height of 2.4 m for each traffic speed can be determined. Using these two results it is possible to calculate the fraction of the total sound energy associated with each of the two source heights as a function of both speed and fraction of heavy vehicles. The fraction associated with each source is then easily reduced to a noise level (in decibels) relative to the total noise.

If a barrier interrupts the propagation of the traffic noise, the attenuation due to the barrier will depend on the difference in height between the top of the barrier and each source; thus the two sources at 0.3 and 2.4 m will be attenuated differently. The resultant level after attenuation by the barrier is obtained by considering each of the sources separately and then combining the two levels.

If the difference between the resultant level behind the barrier and the level in the absence of the barrier is taken as the barrier attenuation, it is possible to invert the calculation and derive the height of a single source which would give the same over-all barrier attenuation as obtained by considering the two sources separately. This height is the effective source height and is a function of speed and fraction of heavy vehicles.

This calculation was performed for 72 different barrier configurations and the arithmetic average of the results taken to obtain the curves is shown in Figure 3.2. The spread in values, of the effective source height, on the average was about ±0.3 m which translates into a possible error of roughly ±1 dB for most practical barrier configurations.

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*This is equivalent to assuming that at 30 km/h the noise emitted from heavy vehicles is essentially due to engine noise alone.

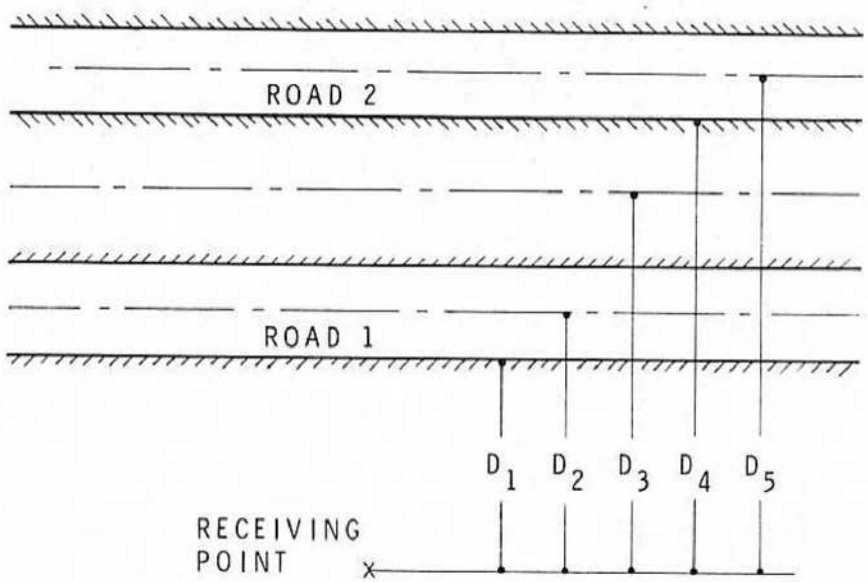


FIGURE 3.1

DETERMINATION OF NOMINAL SOURCE POSITION(S)

$D_1 < \frac{D_3}{2}$ $\therefore$ Road 1 and Road 2 considered separately.

$D_1 > \frac{D_2}{2}$ $\therefore$ Road 1 is line source at distance D_2

$D_4 > \frac{D_5}{2}$ $\therefore$ Road 2 is line source at distance D_5

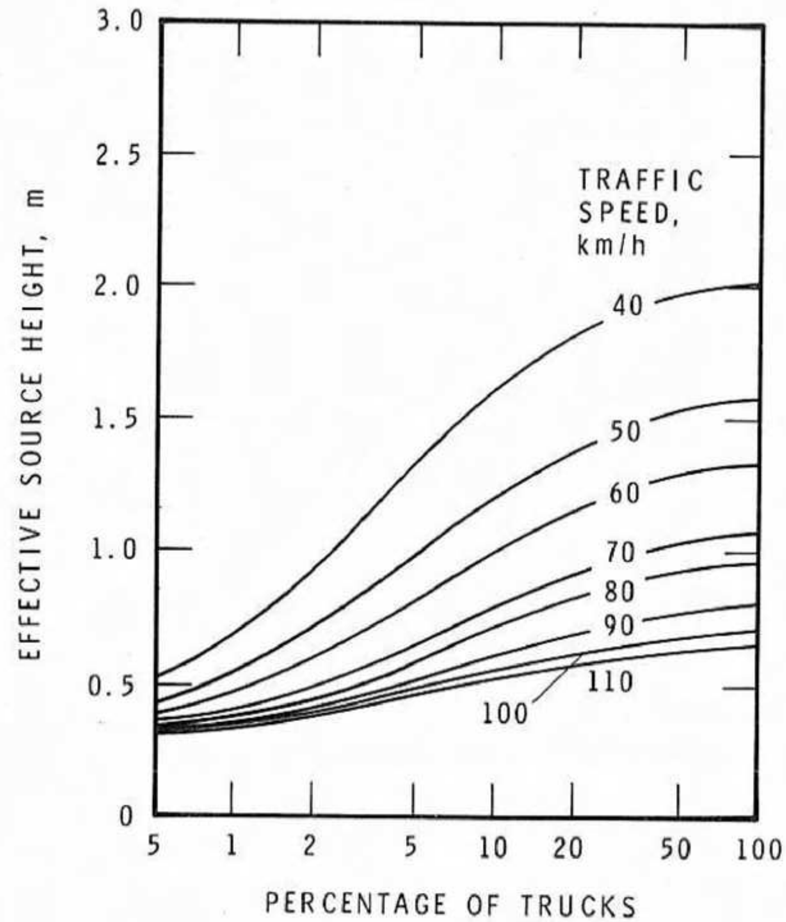


FIGURE 3.2

EQUIVALENT HEIGHT OF TRAFFIC NOISE SOURCE FOR VARIOUS TRAFFIC FLOW CONDITIONS

4. CORRECTIONS FOR DISTANCE AND GROUND ATTENUATION

The preceding two sections are concerned with the prediction of the sound energy emitted by road traffic under various traffic conditions. The predicted value is the nominal sound pressure level that would be observed at a reference point 30 m from the centreline if the ground surface is flat and perfectly reflecting and if the source may be treated as an infinitely long straight line over that surface. It is necessary to provide a means of calculating the sound level at distances other than 30 m from the noise source, and to provide corrections to allow for deviations from the idealized representation of the source and ground surface.

Because materials such as concrete, asphalt, and hard-packed earth provide little acoustical absorption, calculating the propagation over a perfectly reflective surface provides a reasonable estimate of the actual situation in these cases. This estimate is used in the present model if more than half the ground between the source and the receiver has a "hard" surface such as those noted above. In such cases, for a line source the correction for the actual source-receiver distance is given by:

$$\text{Attenuation with distance} = 10 \log (D/30) \qquad [4.1]$$

where D is the horizontal distance in metres from the receiving point to the source.

Although this has the same form as the usual expression for geometrical spreading from a line source, only the horizontal component of the source-receiver distance is used. This results in a predicted incident sound level which is higher than that expected for geometrical spreading by $5 \log (1 + h^2/D^2)$ where h is the height of the receiver relative to the source. This approach was adopted because the design procedure is aimed primarily at predicting the indoor sound level. The effect of using horizontal rather than slant distance is compensated for by the reduction of the facade's sound transmission loss as the range of angles of incidence shifts further from normal incidence. In the idealized case of a limp partition, the noise reduction varies approximately as $10 \log (\cos \theta)$ where θ is the angle of incidence relative to the normal to the facade (11 to 13). For a real wall the dependence on the angle of incidence is more complicated, particularly in those cases where the facade has irregularities such as balconies or recessed windows, but the trend towards lower noise reduction with higher angles of incidence still pertains.

For most suburban situations the difference between horizontal and slant distance is insignificant. There is one obvious situation, however, in which the slant distance tends to be much larger than the horizontal distance, i.e., the case of high-rise buildings in an urban core. In such situations the rate of decrease in the outdoor sound level with increasing receiver height is much less than would be predicted for geometrical spreading from a line source because of multiple reflections from building facades. In these cases the present model (which assumes the outdoor sound level to be independent of receiver height) provides a more accurate prediction of the outdoor level than would result from use of the slant distance.

In most situations, much of the ground surface between the noise source and a building facade may be covered with grass, shrubs, or other vegetation. This causes a further reduction of the sound (in addition to the distance correction of Eq. 4.1) commonly referred to as "excess ground attenuation". Current understanding of the physics of this effect is still incomplete, although the major features can be explained (14,15). A detailed physical evaluation of the ground effect requires a knowledge of atmospheric turbulence and the acoustical impedance of the surface, and involves extensive calculations that would be out of place in a simple prediction model such as this. Fortunately, it is possible to include many of the relevant physical considerations in a simple empirical model. Our treatment of this problem is largely based on a model developed in Sweden (10), with some modifications and extensions to suit present requirements. Figure 4.1 shows the predicted ground attenuation as a function of the distance from the source to the receiving position, and a parameter called the "total effective height". The curves in this Figure are very close approximations to the corresponding curves in Figure 12 of Ref. 10.

The effective total height (denoted H in Eq. 4.2) was introduced to deal with the effect on the ground attentuation of variations in the source or the receiver heights above the ground surface, or the introduction of an obstacle between the source and receiver.

For a noise source close to a flat grassy surface, with no intervening barrier, the effective total height is simply equal to the height of the reciever relative to the ground surface, as shown in Figure 4.2(a). This situation has been extensively studied both theoretically and experimentally and is the case for which the curves of Figure 4.1 were initially formulated (14). For receiver heights more than a few metres above the ground surface, the ground attenuation depends primarily on the angle of the propagation path relative to the surface. For propagation paths very near the ground surface, the attenuation is limited due to the effect of so-called ground and surface waves.

If the noise source is raised appreciably above the surface, the ground attenuation is reduced. As indicated in Figure 4.2(b) this is incorporated in the model by using the sum of source and reciever heights as the effective total height for calculating the ground attenuation. This approach is based on the premise that the angle between the reflected ray and the surface is the primary physical variable determining the ground attenuation, as shown in Figure 4.3. This is equivalent to assuming that ground attenuation, for a given horizontal separation, is determined by the average height above the ground surface of the direct ray from the source to the receiver. In practice, interference between the direct and reflected rays, and other physical considerations lead to some deviations from this model, but it does provide an easy-to-use correction with the appropriate trend. Because much of the noise from road traffic comes from near the road surface, the effect of this adjustment to the effective total height is usually rather small.

A much more significant reduction in the ground attenuation is to be expected if a roadside barrier or other obstruction interferes with sound waves reflected from the surface. In some cases this reduction in ground attenuation may be so large that adding a barrier actually increases the sound reaching some receiver positions (16,17). The calculation of the effective total height for some common configurations is illustrated in Figures 4.2(c) to (g). In these cases it was assumed that the ground attenuation depends on the arithmetic mean of the average heights above the ground surface of the direct ray from the source to the top of the obstruction and the direct ray from there to the receiver. These rules for calculating the effective total height do not deal perfectly with all possible configurations, but do produce the correct trends in most situations as verified by comparison with experimental results.

The resulting effective total height and the horizontal source-receiver distance can then be used to obtain the ground attentuation from Figure 4.1 or from the mathematical expression:

$$\text{Excess ground attenuation} = 8.2 \log\left[\frac{D}{2 + H + H^2/60 + 60/D}\right] - 3 \text{ dB} \qquad [4.2]$$

where D is the horizontal distance from the source to the receiver and H is the "effective total height" (discussed below), both expressed in metres. This correction is applied in this model when more than half the ground surface between the source and receiver is acoustically "soft", and is subject to the following mathematical limits:

(a) If H is less than 1.5 m, the value H = 1.5 is used.
(b) If D is greater than 400 m, the value D = 400 is used.
(c) If the value calculated using Eq. 4.2 is negative, the excess ground attenuation = 0 dB.

This, together with the predicted noise level at 30 m from the centreline, and the distance attenuation correction of Eq. 4.1 yields the predicted sound level at the receiving point, in the absence of a barrier.

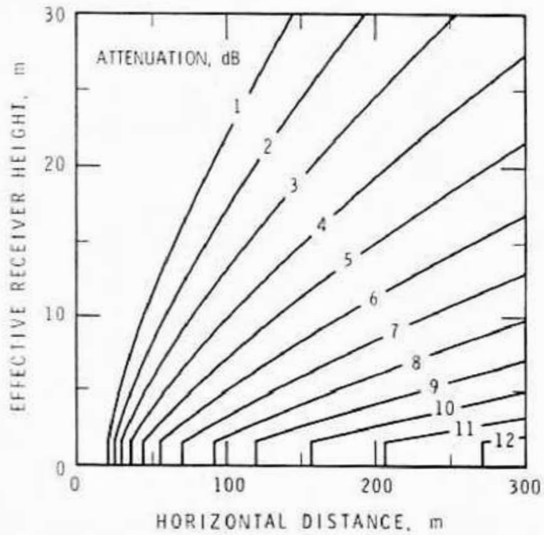


FIGURE 4.1

CORRECTION TO PREDICTED L_{eq} TO ALLOW FOR GROUND ATTENUATION

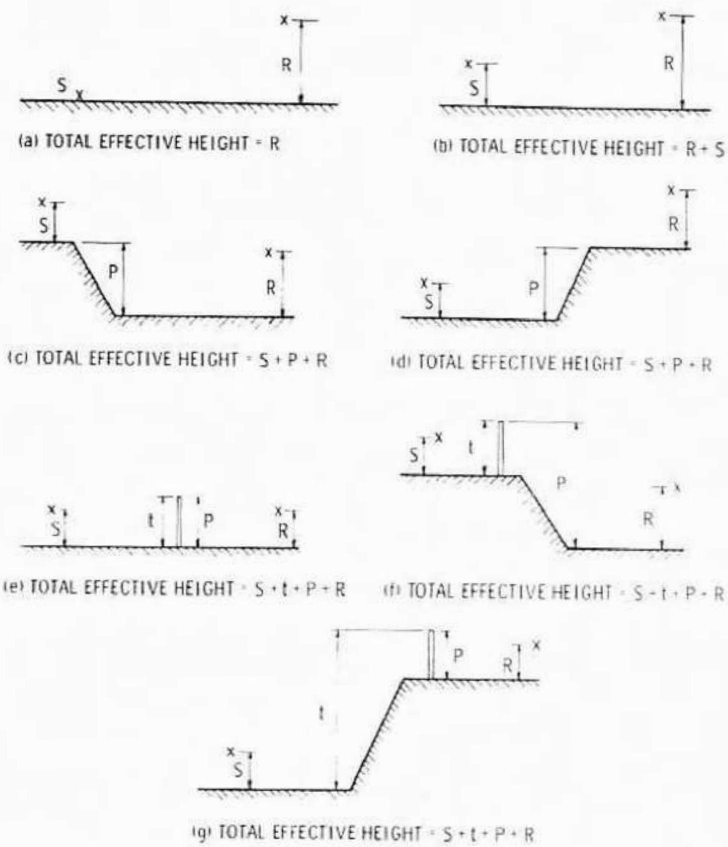


FIGURE 4.2

CALCULATION OF TOTAL EFFECTIVE HEIGHT FOR SOME COMMON CONFIGURATIONS

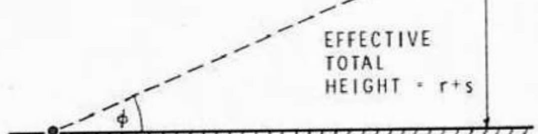


FIGURE 4.3

DETERMINING EFFECTIVE TOTAL HEIGHT FOR GROUND ATTENUATION CALCULATIONS

5. ATTENUATION BY AN INFINITELY LONG BARRIER

The most widely used model for predicting barrier attenuation is that developed by Maekawa for a point noise source above a hard ground surface (18). It is based on experimental data, but an approximate analytical expression in terms of the Fresnel number (N) has been derived (19). Although there is an inherent frequency dependence of the barrier attenuation, it is commonly assumed that the barrier attenuation for A-weighted traffic noise can be approximated by the attenuation at 500 Hz, for which $N = 2\delta/\lambda = 3.3\delta$ where δ is the path length difference and λ is the wavelength in metres (19). With this substitution, the barrier attenuation for a point source can be expressed as:

$$\begin{aligned} \text{Barrier attenuation} &= 20\ \log[\sqrt{21\delta}/\tanh\sqrt{21\delta}] + 5\ \text{dB, for } \delta>0 \\ &= 20\ \log[\sqrt{21}|\delta|/\tan\sqrt{21}|\delta|] + 5\ \text{dB, for } -0.6\text{m} < \delta < 0 \\ &= 0\ \text{dB, for } \delta < -0.06\ \text{m} \end{aligned} \qquad [5.1]$$

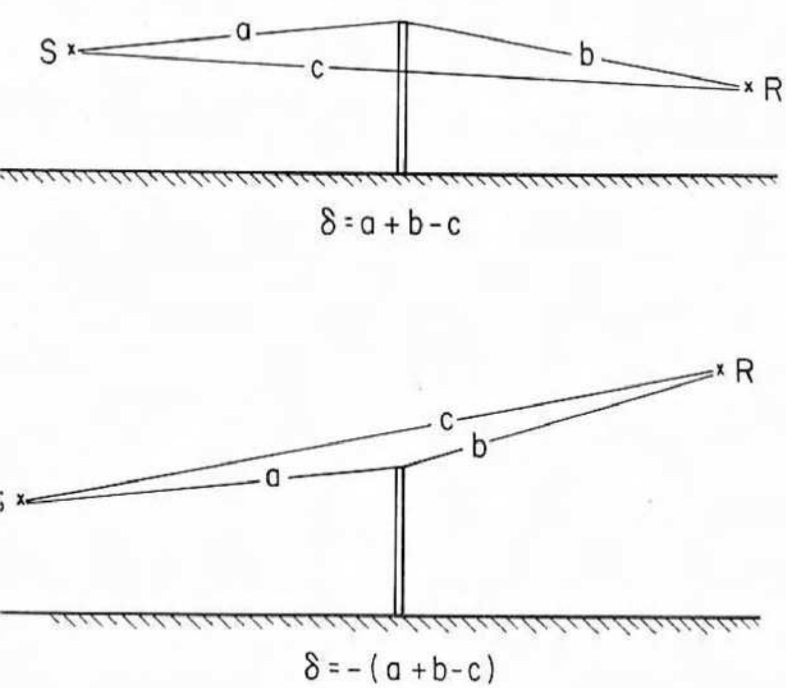
A further extension was provided by Kurze and Anderson who considered the case of an incoherent line source (19). Their analysis was subject to four major simplifying assumptions:

1. The source is an infinitely long, straight incoherent line source of uniform strength per unit length.
2. The barrier is of uniform height throughout its length and is parallel to the source.
3. No effects such as turbulence or atmospheric absorption are associated with the propagation medium.
4. The ground surface is flat and perfectly reflecting.

Although these assumptions permit a straightforward mathematical treatment of the problem, they do not apply very well to the conditions actually encountered in roadside barrier applications. Hence a somewhat different treatment of barrier attenuation has been adopted for the present model. Because it is believed that reflections from other surfaces and atmospheric effects such as wind and turbulence will limit the effectiveness of a barrier, an upper limit of 20 dB was put on the predicted barrier attenuation. For the other extreme, the original CMHC model made the simplifying assumption that attenuation approached zero at zero path length difference, but recent extensive observations (20) demonstrated that this was an over-simplification. Accordingly, it was necessary to extend the model to include negative path length differences, i.e., receiving points that lie outside the geometrical shadow zone of the barrier as shown in Figure 5.1. Although the barrier does not interrupt the direct sound ray, diffraction from the barrier edge may provide up to 5 dB of attenuation for small negative values of δ. A smooth transition from 0 dB to 5 dB of barrier attenuation, essentially consistent with the point source expression in Eq. 5.1, was developed.

In the intermediate situations where barrier attenuation is between 5 dB and 20 dB, an appreciable scatter in the performance of barriers may be expected. On the one hand, effects such as atmospheric absorption and ground attenuation tend to produce higher attenuations than would be predicted from the Kurze and Anderson result, as discussed in Section 6.2. On the other hand, reflections from nearby buildings tend to reduce the attenuation at most urban and suburban sites. Depending on its direction, wind may increase or decrease the effective attenuation, but the decreases in attenuation tend to be more significant (16, 17). Bearing these considerations in mind, an expression that predicts slightly lower barrier attenuations than the Kurze and Anderson result was selected. The predicted attenuation may be obtained either from Figure 5.2 or from the equations:

$$
\text{Barrier attenuation} = \begin{cases} 20 \text{ dB} & \text{, for } \delta > 6 \text{ m} \\ 7.7 \log\delta + 14 \text{ dB} & \text{, for } .3 \text{ m} < \delta < 6 \text{ m} \\ -10.4(\delta + .06) + 22.8(\delta + .06)^{\frac{1}{2}} & \text{, for } -.06 \text{ m} < \delta < .3 \text{ m} \\ 0 & \text{, for } \delta < -.06 \text{ m} \end{cases}
$$



IGURE 5.1

ETERMINING THE PATH LENGTH DIFFERENCE, δ,
OR A BARRIER

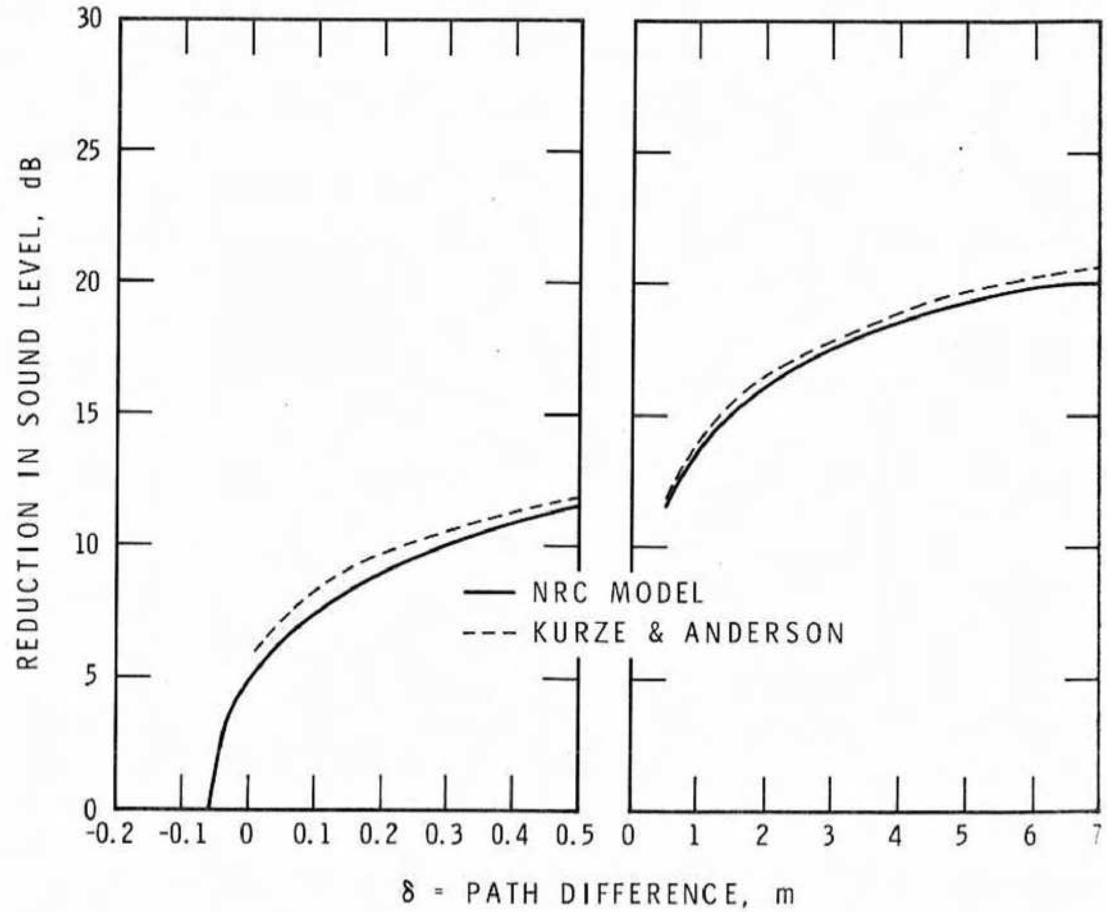


FIGURE 5.2

PREDICTED REDUCTION IN L_{eq} PROVIDED BY A BARRIER OF INFINITE LENGTH

6. BARRIERS OF FINITE LENGTH

A barrier of finite length provides less sound attenuation than an infinitely long barrier because of the sound energy coming past the ends of the barrier. The fraction of the total received sound energy that comes around the ends of a barrier depends not just on the position and size of the barrier but also on the type of ground surface. The limiting cases with a perfectly reflecting surface and with an absorptive surface are analysed in the following subsections, and the intermediate solution used in this model is presented.

6.1 Barrier End Corrections (Hard Ground Surface)

In the simple case where the ground surface is assumed to be flat and perfectly reflecting, it is a straightforward problem to determine the attenuation provided by a barrier of finite length. The line source may be treated as a set of incoherent line segments and the sound energy reaching the receiver from all of these segments combined to give the resultant sound level.

The geometry of the problem is shown in Figure 6.1. For propagation over a flat perfectly reflecting surface, in the absence of barrier attenuation (or any other attenuation except geometrical spreading), it can be shown that equal sound energy reaches R from any segment of the line source subtending $d\theta$, independent of the angle θ. Each segment $d\theta$ (expressed in degrees) contributes $d\theta/180$ of the total sound energy arriving at R from the line source. If a barrier is introduced between the receiver and a given source segment, the sound energy from that segment is then reduced to $b_\theta\ d\theta/180$ where

$$b_\theta = \text{antilog}(-B_\theta/10) \qquad [6.1]$$

and B_θ is the appropriate barrier attenuation for that segment. If $d\theta$ is sufficiently small, the segments may be treated as point sources and the Maekawa expression for barrier attenuation with a point source may be used for B_θ. For an infinitely long barrier parallel to the line source, numerical. integration using this procedure yields the result obtained by Kurze and Anderson for an incoherent line source.

For all the calculations discussed below, the line source was divided into 60 segments each subtending an angle $d\theta$ of 3 degrees; for the case of an infinitely long barrier, this was found to give essentially the same result as the use of 1 degree increments and it provided reasonable resolution for evaluating the effect of shortening the barrier. The barrier attenuation was calculated using the expression

$$\text{Barrier attenuation} = -10\ \log(\sum_\theta b_\theta d\theta / \sum_\theta d\theta) \qquad [6.2]$$

where θ ranges from -88.5 degrees to +88.5 degrees and $b_\theta = 1$ if that segment of the source is visible beyond the end of the barrier. The results of these calculations are presented in Figure 6.2 as a function of the angle subtended by the barrier at the receiving point.

6.2 Barrier End Corrections (With Ground Attenuation)

Ground attenuation lessens the change in barrier attenuation caused by reducing the length of the barrier. The fraction of the total energy that comes from the more distant segments of the line source is reduced by the ground effect, and therefore the change in sound energy caused by the barrier screening those segments is a smaller fraction of the total sound energy than it would be for the hard ground case. In addition, the decreased attenuation associated with removing a segment of the barrier is partially offset by increased ground attenuation because the height of the propagation path is decreased for that segment.

In order to proceed with a calculation of the effect of barrier length, an expression for ground attenuation with a point source was required. For the simple case with a point source at the ground surface, the ground attenuation is given approximately by:

$$\text{Ground attenuation} = -20\ \log[(\frac{2Z_2}{Z_1})\sin\psi] \qquad [6.3]$$

where Z_1 is the characteristic impedance of air and Z_2 is the acoustic impedance of the surface (14). Although the equation is nominally for the case where the source is on the ground plane, defining the angle ψ as the arctangent of the ratio of effective total height to horizontal distance would introduce a dependence on the source height or obstruction height formally equivalent to that presented in Section 4. It must be recognized, however, that Eq. 6.3 is a simplified expression for a very complex phenomenon, and is not fully satisfactory, particularly for small values of ψ where surface wave effects introduce a further complication. The expression was therefore recast in the form

$$\text{Ground Attenuation} = 20\ \log[a\ \sin(\psi + b + \frac{c}{D})] \qquad [6.4]$$

where D is the horizontal source-receiver distance, and a, b and c are coefficients selected to minimize differences between the line source expression of Eq. 4.2 and the result of integrating this point source expression along a line source. Although a perfect fit is not possible with this functional form, the error does not exceed 1 dB in the range covered in Figure 4.1 if the coefficients are given the values a = 15.5, b = .011, c = .35 and negative attenuations are treated as 0 dB.

Following the same approach to the calculation of barrier end effects as was used in Part 6.1, the sound energy reaching the receiver from a given segment of the line source is $b_\theta g_\theta d\theta$ where the expression g_θ corresponding to Eq. 6.4 takes the form:

$$g_\theta = [15.5\ \sin(\psi + .011 + .35/D)]^{-2} \qquad [6.5]$$

where both the angle ψ and the horizontal distance D depend on θ. The attenuation for a barrier of finite length is given by the expression:

$$\text{Barrier Attenuation} = -10 \log \left[\frac{\sum\limits_{\theta} b_\theta g_\theta d\theta}{\sum\limits_{\theta} d\theta} \right] - \left\{ -10 \log \left[\frac{\sum\limits_{\theta} g'_\theta d\theta}{\sum\limits_{\theta} d\theta} \right] \right\} \qquad [6.6]$$

subject to the same conditions on $d\theta$, b_θ and the summation over θ as were noted for Eq. 6.2. The second term in Eq. 6.6 is the ground attenuation that would be predicted in the presence of an infinitely long barrier. To maintain consistency with the line source model, this must be subtracted off to obtain that portion of the excess attenuation associated specifically with "barrier attenuation". The ground attenuation expression is denoted g'_θ in the second term to indicate that for each θ it is calculated using an effective total height that includes barrier height. In the first term $g_\theta = g'_\theta$ if the source segment at θ is behind the barrier, but was otherwise calculated using the smaller effective total height applicable in the absence of a barrier.

Equation 6.6 was evaluated for a receiver behind the midpoint of a barrier subtending angles ranging from 0 to 180 degrees in steps of 6 degrees. Because of the interaction of ground effect and barrier attenuation, the results obtained depend on the positions of the barrier and receiver relative to the source. The calculations were performed for the 77 configurations noted in Table 6.2, and the mean results (averaged over all configurations) are presented in Figure 6.3. The nominal barrier attenuation indicated on the curves in Figure 6.3 is the attenuation obtained by integrating the expression of Eq. 6.2 for an infinitely long barrier (which is essentially the same as the line source result of Kurze and Anderson). Figure 6.4 shows the range of values for the specific case with nominal barrier attenuation of 20 dB, to provide an indication of the variation associated with changes in the configuration. The curves have limiting values for very short and very long barriers, that (at least at first glance) are quite disturbing.

Table 6.2

Positions of Barrier and Receiver (Relative to the Source) Used for Calculating Figure 6.3

Source-Receiver Distance (ft)	Source-Barrier Distances (ft)	Receiver Heights (ft)
100	30, 50	0, 5, 10, 15, 20, 25, 30
200	30, 50, 100	0, 5, 10, 15, 20, 25, 30
400	30, 50, 100	0, 5, 10, 15, 20, 25, 30
800	30, 50, 100	0, 5, 10, 15, 20, 25, 30

For a barrier of zero length, this calculation predicts a significant barrier attenuation as illustrated in Figure 6.3. This attenuation is simply the difference between the ground attenuation in the absence of a barrier (the first term in Eq. 6.6) and the ground attenuation with an infinitely long barrier (the second term in Eq. 6.6). This might be described as the situation where a telephone pole is treated as a barrier. The ground attenuation calculation (as presented in Section 4) allows for only two cases: a barrier is, or is not, present. Implicitly, if there is a barrier the ground effect is adjusted as if that barrier were affecting propagation from the entire line source. Thus in the case of a short barrier the basic ground effect calculation underestimates the ground attenuation for those portions of the source beyond the ends of the barrier. The apparent attenuation for a barrier of zero length is the appropriate adjustment of the ground attenuation.

The second apparent problem with the curves in Figure 6.3 is that the calculated barrier attenuation for a very long barrier is greater than the nominal value. This difference arises because barrier attenuation and ground attenuation are not simply additive. The nominal attenuation for an infinitely long barrier was obtained using Eq. 6.2 (or the Kurze and Anderson result) which applies if the ground surface is hard. Including the ground attenuation provides more attenuation for the more distant segments, and therefore increases the fraction of the total sound energy coming to the receiver from the nearest source segments. These are the segments for which the path length differences (and hence the barrier attenuation) are largest. Thus the effective "average" barrier attenuation should be somewhat larger than is expected for a line source on hard ground. In general, the result should lie somewhere between the Kurze and Anderson result and that predicted by Maekawa for a point source.

6.3 Barrier End Corrections (Typical Applications)

To simplify the calculations in the CMHC design procedure, a single correction, to be used in both the hard and soft ground cases, was desired. Because most sites in urban and suburban areas have some ground surface of both types, this compromise is generally preferable to either of the extremes considered above. The resulting curves agree with the hard ground result in the limits of very long or very short barriers, and lie between the hard ground and soft ground results for intermediate cases.

Because barriers are seldom symmetric about the receiving point of interest, a set of curves appropriate for evaluating the effect of sound coming around only one end of the barrier is given in Figure 6.5. The attenuation provided by a barrier of finite length in both directions is obtained by correcting first for the short end of the barrier and then using that adjusted attenuation as the nominal barrier attenuation when calculating the correction for the other end. The curves in Figure 6.5 show the attenuation as a function of the "barrier aspect ratio"; calculation of this ratio is illustrated in Figure 6.6.

The situation may arise where there is a barrier shielding part of the road from the receiving point, but the barrier does not intersect the line from the receiver to the nearest point on the road, as illustrated in Figure 6.7. In this case a first approximation of the barrier attenuation is calculated in the manner described previously, using barrier aspect ratios of 0 and arctan (θ_2). This result is then multiplied by

$(1 - \theta_1/\theta_2)$ to obtain the predicted barrier attenuation. It should be noted that the barrier attenuation in such cases is never more than 3 dB, and is less than 1 dB if the angle subtended by the barrier is less than 30 degrees. If the predicted barrier attenuation is less than 2 dB, it is generally more accurate to ignore the barrier and apply only a ground attenuation correction (omitting the barrier in evaluating the effective total height).

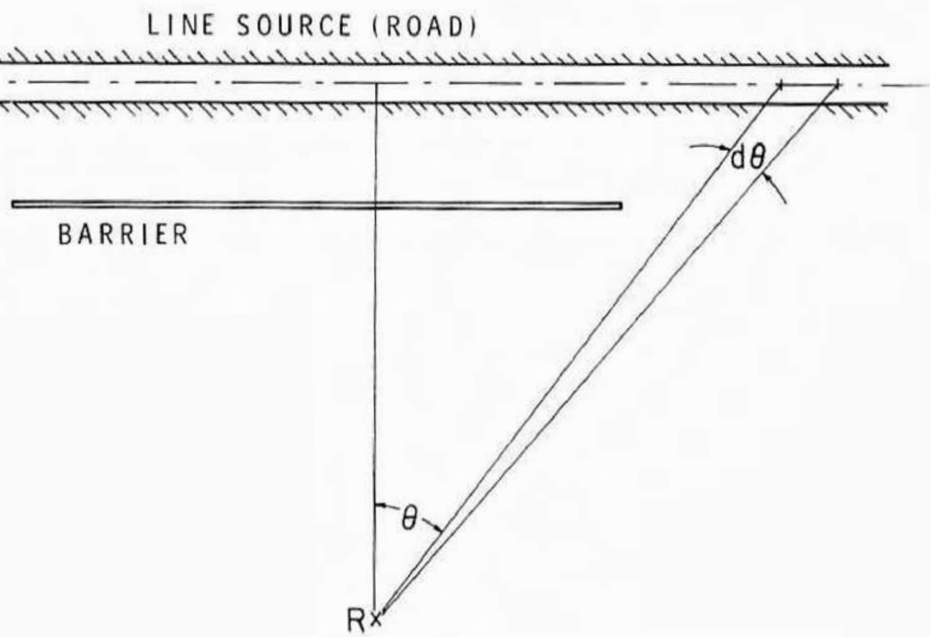


FIGURE 6.1

GEOMETRICAL CONSIDERATIONS FOR BARRIER END CORRECTION

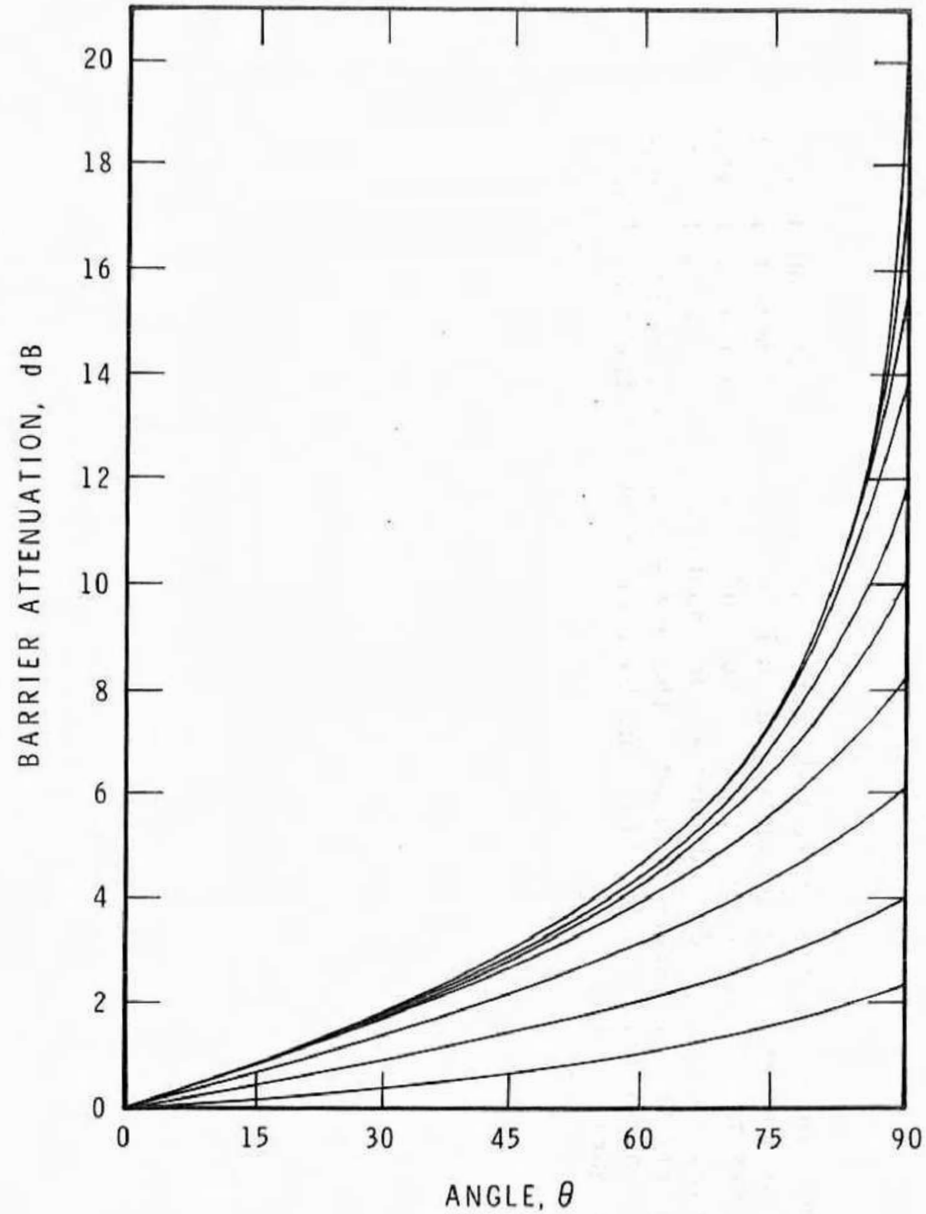


FIGURE 6.2

BARRIER ATTENUATION FOR SYMMETRIC BARRIERS SUBTENDING THE ANGLE 2θ FOR PROPAGATION OVER HARD GROUND

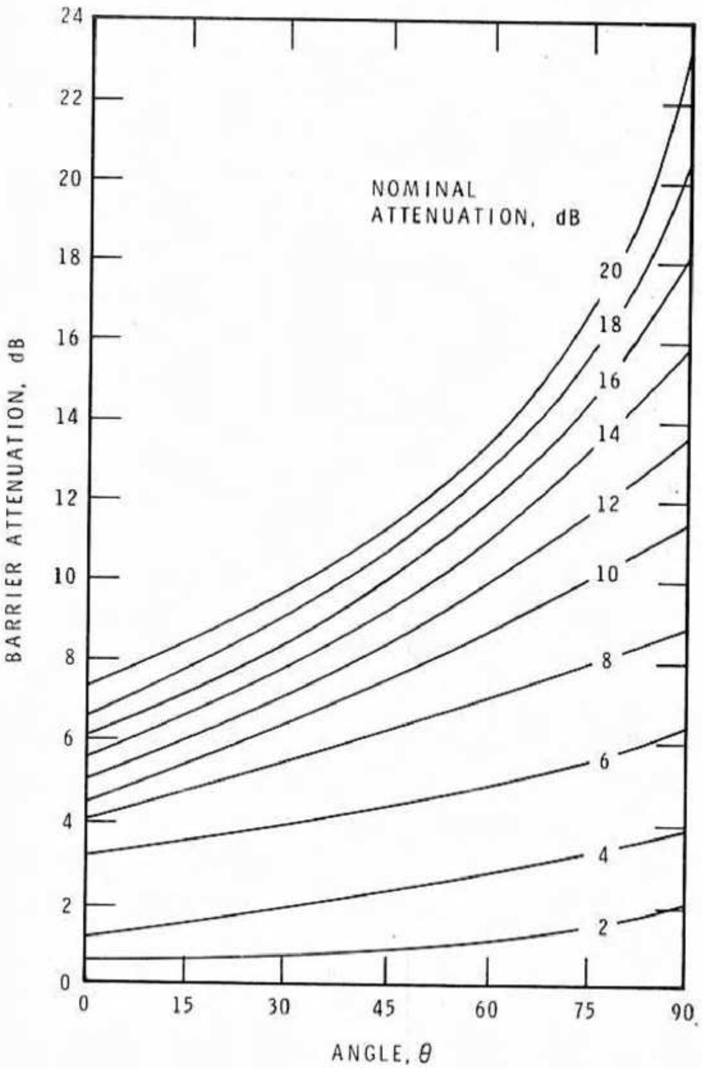


FIGURE 6.3

BARRIER ATTENUATION FOR SYMMETRIC BARRIERS SUBTENDING THE ANGLE 2θ FOR PROPAGATION OVER SOFT GROUND

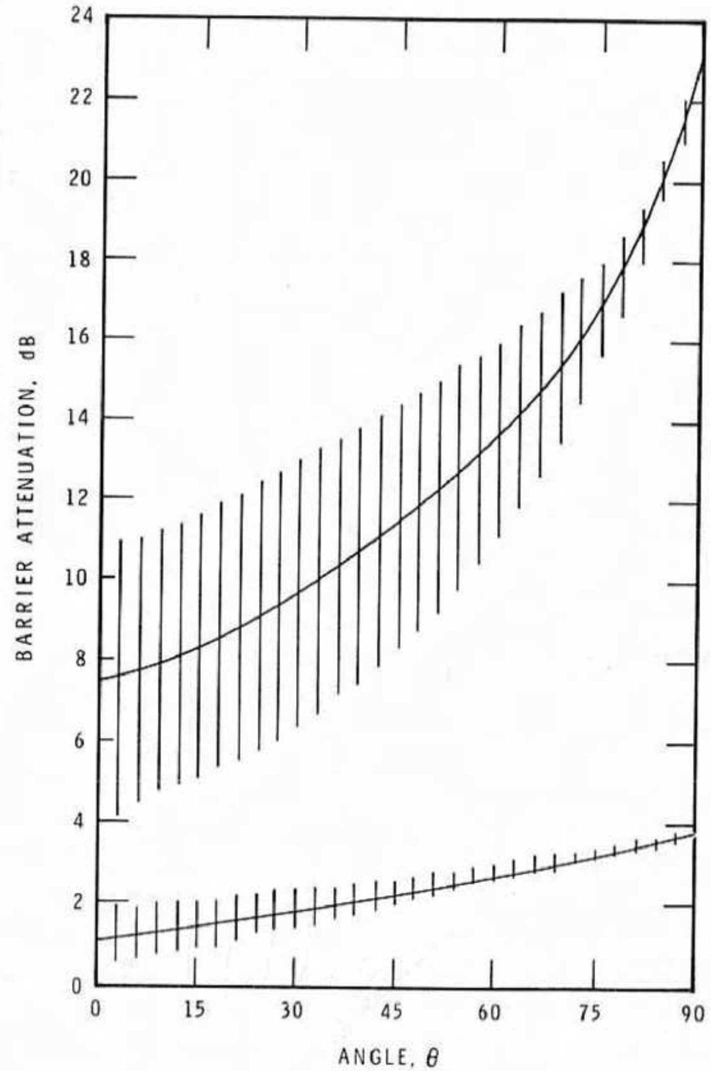


FIGURE 6.4

BARRIER ATTENUATION FOR SYMMETRIC BARRIERS FOR PROPAGATION OVER SOFT GROUND, SHOWING THE RANGE OF VALUES FOR NOMINAL 20 dB AND 4 dB ATTENUATION BARRIERS

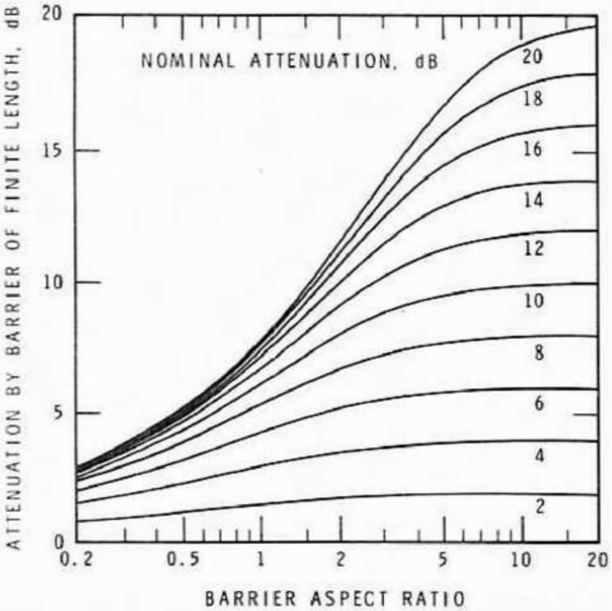


FIGURE 6.5

CORRECTION TO THE BARRIER ATTENUATION TO ALLOW FOR SOUND COMING AROUND ONE END

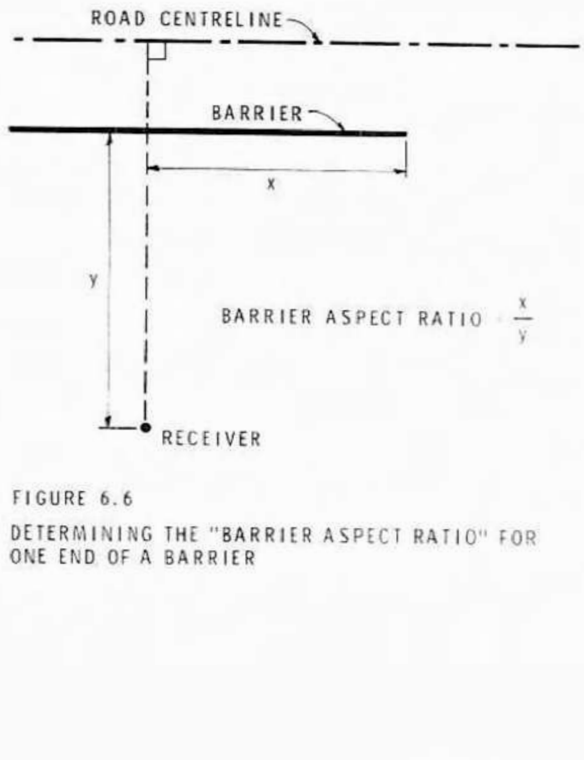


FIGURE 6.6

DETERMINING THE "BARRIER ASPECT RATIO" FOR ONE END OF A BARRIER

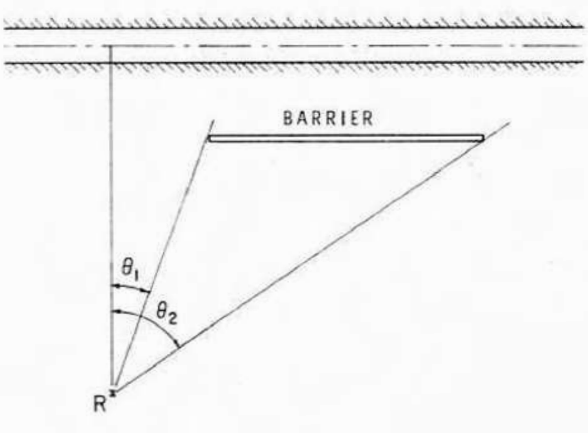


FIGURE 6.7

DETERMINING ANGLES FOR OFFSET BARRIER

7. CURVES AND SEGMENTED BARRIERS

The prediction scheme described so far assumes that the roadway under consideration is straight and infinitely long. This assumption is adequate in most situations, but there are many cases where allowance must be made for other than a straight road.

It can be shown that for the case of an infinitely long, straight line source on a smooth perfectly reflecting plane the sound energy reaching a point due to any line segment depends only on the angle subtended by that segment. That is, line segments subtending equal angles contribute equal sound energy. This is no longer true if there is ground attenuation, as in this case the segments closer to the receiving point contribute proportionately more energy. For the purposes of this model, however, it will be assumed that the rule of equal angles contributing equal energy gives an adequate approximation. On this basis a procedure can be developed to deal with curved roads such as that portrayed in Figure 7.1.

The roadway shown in Figure 7.1 can readily be treated as two straight road segments, numbered 1 and 2, each of which contributes sound energy to the receiving point P. The analysis is now straightforward. Let L_1 be the sound level predicted at point P if road 1, at distance D_1, were the only road contributing, and L_2 be the sound level predicted at point P if road 2, at distance D_2, were the only road contributing. The fraction of the sound energy from road 1 which actually does contribute is given by $\theta_1/180$ and from road 2, by $\theta_2/180$ (if the equal angle, equal energy rule is applied). Thus the sound level at point P is given by

$$L = 10 \log \left[\frac{(10^{L_1/10})\theta_1}{180} + \frac{(10^{L_2/10})\theta_2}{180}\right] \qquad [7.1]$$

In more complicated situations it may be necessary to decompose the roadway into more than two straight roads, however the extension of the procedure is straightforward.

A slightly different although closely related problem is that of a long barrier with gaps in it, such as a row of buildings between the receiving point and the roadway under consideration. In this case L_1 is the level predicted for the situation with a continuous barrier and L_2 is the level predicted in the absence of the barrier. The angle θ_1 subtended by the barrier is obtained by adding the angles subtended by each of the barrier segments, and the angle θ_2 associated with the gaps is obtained from $\theta_2 = 180 - \theta_1$. The resultant level is now easily obtained by using Eq. 7.1.

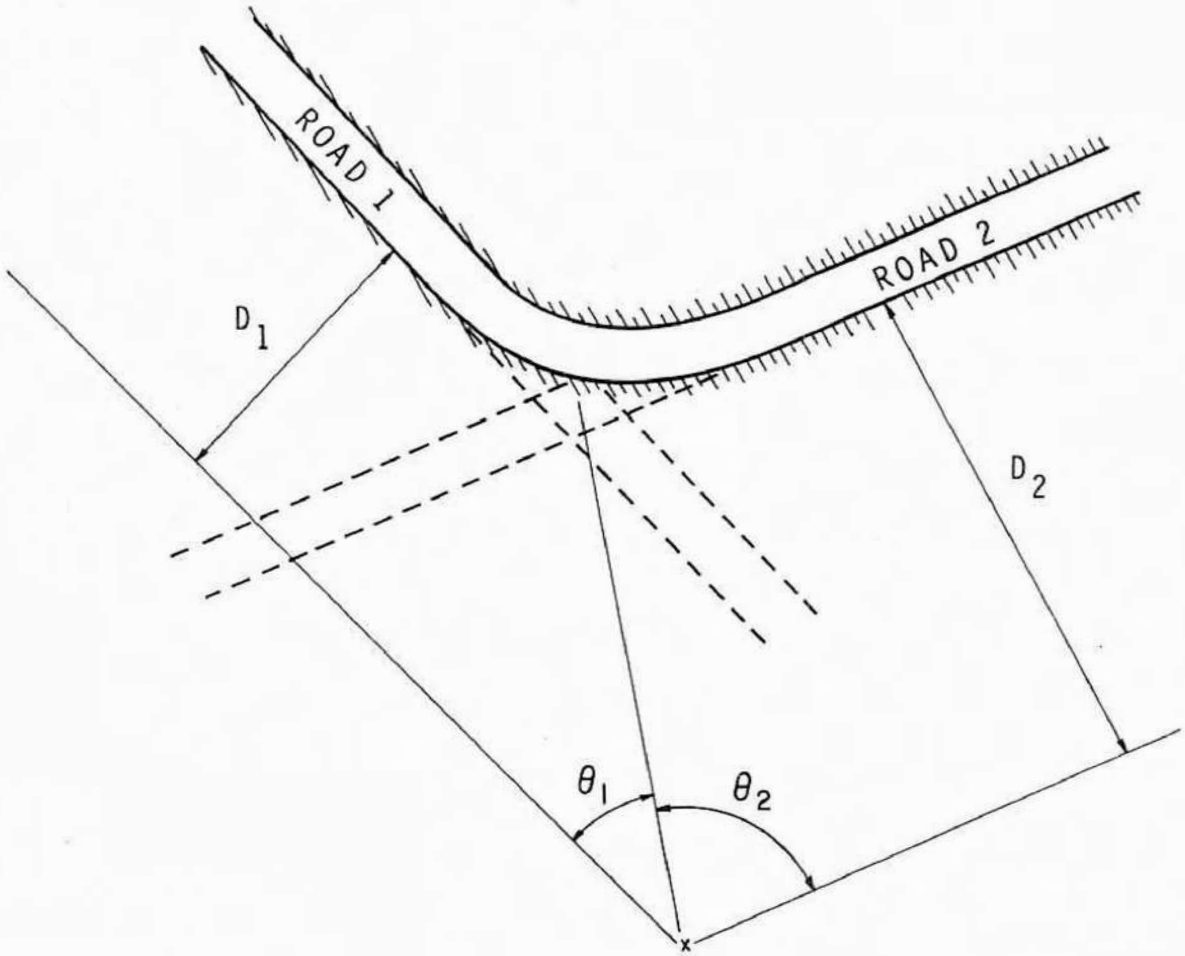


FIGURE 7.1

SEPARATION OF CURVED ROAD INTO TWO ROADS. ROAD 1 AT DISTANCE D_1, SUBTENDING ANGLE θ_1 AND ROAD 2 AT DISTANCE D_2, SUBTENDING ANGLE θ_2

8. INTERRUPTED FLOW

The traffic noise source levels calculated in Section 1 are based on the assumption that the traffic is flowing freely at constant speed. While this is usually the situation on freeways, it is not the situation on most urban roadways where traffic lights and stop signs are used to control traffic flow and speed.

The emitted sound power from each vehicle decreases as the vehicle decelerates approaching the stop, increases to a maximum as the vehicle accelerates away from the stop, and finally settles back to the level characteristic for free-flowing traffic when the vehicle reaches its cruising speed. The equivalent sound level follows a slightly different pattern, because the slower motion of the vehicles near the stop results in their spending a longer time interval (with a corresponding increase in the integrated sound energy) in the segments of the road near the stop.

Field measurements with single vehicles (21) and computer studies for single lanes of vehicles (22) suggest that very close to the roadside there is a maximum decrease in the equivalent sound level of 1 to 2 dB on the approach to a traffic light and a maximum increase of about 5 dB on the accelerating side. If two lines of vehicles travelling in opposite directions are considered then there is a resultant increase in equivalent sound level of up to 3 dB for a short distance in both directions from the traffic light, when measured at a distance of under 10 m from the roadside.

On the basis of these studies, the increase in the time-averaged sound power emitted from the source has been assumed to have a profile as shown in Figure 8.1 in the region about the traffic light. This profile ignores any traffic on the cross street. The distance X_2 depends on the stopping distance and acceleration rate and is therefore a function of both the speed limit and vehicle type. The values given in Table 8.1 are a first approximation of the appropriate values for automobiles, obtained from Ref. (23). Information on comparative stopping distances and accelerations suggests that X_2 is approximately five times as large for heavy vehicles as for automobiles travelling at the same speed.

Table 8.1

Distance Travelled during Acceleration
(from test for some common speeds)

Speed (km/h)	Distance to reach Speed X_2 (m)
50	100
70	175
90	275

The sound level at any receiving point was obtained by dividing the road into segments and combining the sound energy received from all increments (using an appropriate propagation loss). The excess level due to the traffic light is simply the difference between the integrated sound energy predicted using the profile of Figure 8.1 and that obtained when all segments emit the sound energy characteristic of freely flowing traffic. A decrease of 9 dB per doubling of the distance from the segment midpoint was assumed. The difference of 3 dB/doubling from the usual correction for spreading from a point source was included to allow for ground attenuation, screening by buildings, and other sources of excess attenuation. The resulting change in the equivalent sound level was given by the expression:

$$L(D,X) = 10 \log \int_{-\infty}^{\infty} \frac{10^{L(x)/10} dx}{(D^2 + (x - X)^2)^{3/2}} - 10 \log \int_{-\infty}^{\infty} \frac{10^{L/10} dx}{(D^2 + (x - X)^2)^{3/2}}$$

where X = distance parallel to roadway from traffic light to receiving point,

D = source-receiver distance perpendicular to roadway

L = equivalent sound level 8 m from centreline in absence of traffic light,

$L(x)$ = sound level corresponding to L, with traffic light (Figure 8.1).

This expression was evaluated numerically for both light and heavy vehicles and speed limits of 50, 70 and 90 km/h with appropriate values of x_2. It was found that by scaling the distances D and X by the factor $(1 + \sqrt{T})(S^2/2500)$, where T is the fraction of heavy vehicles and S is the speed limit in km/h, all the results could be presented in the single plot of excess level vs normalized position given in Figure 8.2.

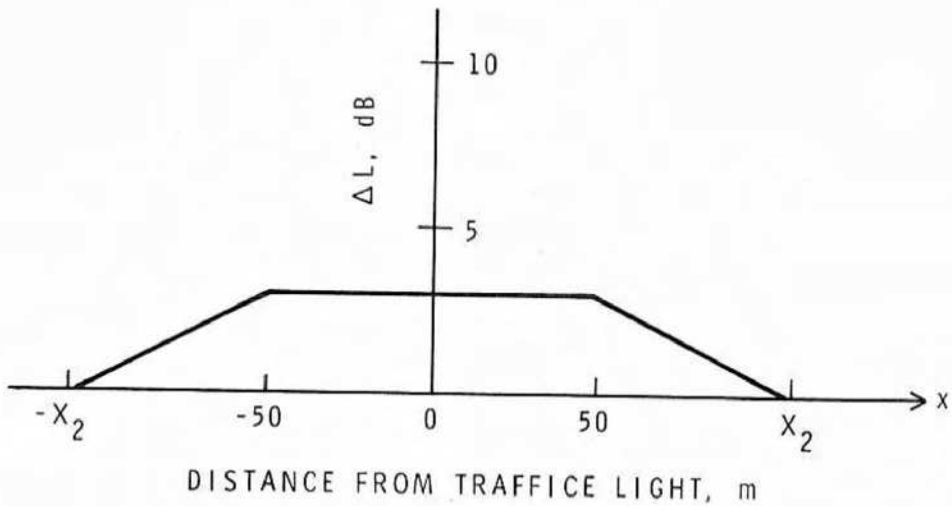


FIGURE 8.1

INCREASE IN SOUND LEVEL $\Delta L(x)$ ASSOCIATED WITH THE INSERTION OF A TRAFFIC LIGHT

$$
\Delta L(x) = \begin{cases} 0 & x \le -X_2 \\ \dfrac{3(X_2 + x)}{(X_2 - 50)} & -X_2 < x \le -50 \\ 3 & -50 < x < 50 \\ \dfrac{3(X_2 - x)}{(X_2 - 50)} & 50 \le x < X_2 \\ 0 & x \ge X_2 \end{cases}
$$

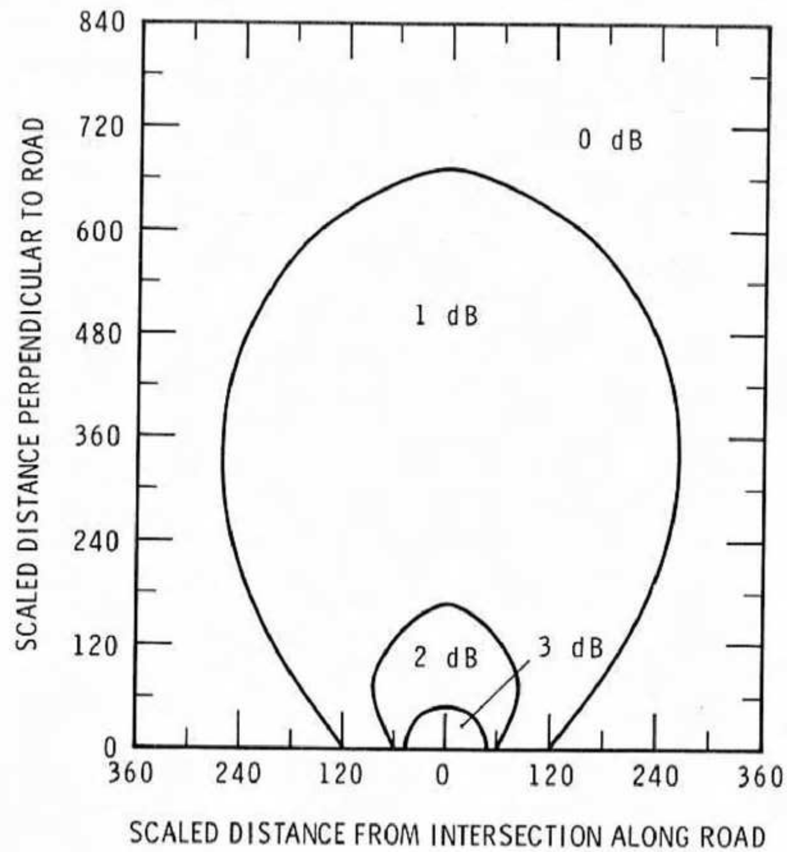


FIGURE 8.2

CORRECTION TO BE ADDED TO PREDICTED L_{eq} TO ALLOW FOR NEARBY TRAFFIC LIGHTS OR STOP SIGNS.

$$
\text{SCALED DISTANCE} = \frac{\text{ACTUAL DISTANCE}}{(1 + \sqrt{F})\,(S^2/2\,500)}
$$

WHERE F IS THE FRACTION OF HEAVY VEHICLES AND S IS THE POSTED SPEED LIMIT, IN km/h

9. NOISE EMITTED BY RAILWAY TRAFFIC

The noise emitted during the passby of railway trains can be broken into three main components; locomotive engine and exhaust noise; wheel-rail interaction noise; and whistle noise.

Several methods have been proposed (24 to 28) for predicting train passby noise, although not all pertain to diesel-electric locomotives such as are used in Canada. The basic expressions used here were developed by the Ontario Ministry of the Environment based upon passby measurements made in southern Ontario (28).

9.1 Locomotive Exhaust Noise

Calculation of the noise level caused by locomotive exhaust requires the knowledge of two parameters: the speed and the loading of the locomotive (i.e., the number of cars per locomotive). The maximum passby level, measured at 15 m from track centreline, is given by:

$$\begin{aligned} L_{max}(15\text{ m}) &= 82.8 + 0.15\,x &&,\ S < 30\text{ km/h} \\ &= 49.1 + 0.15\,x + 23.5\,\mathrm{Log}(S), &&\ S \geq 30\text{ km/h} \end{aligned} \qquad [9.1]$$

where S is speed in km/h, and x is the loading in cars per locomotive. For a receiver at distance D, a locomotive may be considered as a point source, and in the absence of excess attenuation the maximum passby sound level is:

$$L_{max}(D) = L_{max}(15\text{ m}) + 20\log\left(\frac{15}{D}\right) \qquad [9.2]$$

The equivalent sound level at 30 m for a single locomotive passby can be obtained by integration over the passby time. Allowing for the locomotive length of 17 m, and normalizing to 24 hours gives:

$$\begin{aligned} L_{eq,L} &= 10\log N - 10\log S + 0.15\,x + 52 &&,\ S < 30\text{ km/h} \\ &= 10\log N + 13.5\log S + 0.15\,x + 16.5, &&\ S > 30\text{ km/h} \end{aligned} \qquad [9.3]$$

where N is the number of locomotives/24 h, and S and x are defined above.

These equations can be rewritten in the form

$$L_{eq_1} = 10\log N + K + 16.5 \qquad [9.4]$$

where K is a load parameter given by:

$$\begin{aligned} K &= 13.5\log S + 0.15\,x &&,\ S < 30\text{ km/h} \\ K &= -10\log S + 0.15\,x + 35.5, &&\ S > 30\text{ km/h} \end{aligned} \qquad [9.5]$$

Figure 9.1 shows a plot of L_{eq} vs the number of locomotives for representative values of the load parameter K.

For the purpose of ground attenuation and barrier attenuation calculations the locomotive exhaust noise is taken to be located 4 m above the railway track, and the calculations are performed exactly as discussed previously for road traffic noise.

9.2 Rolling Noise

The interaction between steel railway wheels and the steel rail is the other major source of noise from railways. This is aggravated by joints between rail sections, switches and the squeal of the wheel flanges rubbing curves. Only the noise associated with trains rolling on straight jointed track is considered here, the problem of switch noise and wheel squeal will in general be dealt with better by field measurements.

The maximum passby level at 15 m for rolling noise is given by:

$$L_{max}(15\ m) = 87.8 + 25.7 \log \frac{S}{97} \qquad [9.6]$$

where S is train speed in km/h.

The equivalent level at a distance d may be obtained by integration, assuming that the track is straight and that the distance is greater than the length of the rail car (usually ~ 17 m).

$$L_{eq} = 87.8 + 25.7 \log \left(\frac{S}{97}\right) + 10 \log \left(\frac{15}{D}\right) \qquad [9.7]$$

This can now be extended to give the 24-h equivalent level for railway cars at 30 m.

$$L_{eq,R} = 8.8 + 10 \log n + 15.7 \log S \qquad [9.8]$$

where n is the number of railway cars/24 h. The 24-h equivalent level is plotted in Figure 9.2 as a function of the number of railway cars for a variety of different speeds.

The rolling noise, although primarily due to the interaction of the wheels with the rails, also contains a significant contribution from rattle of the suspension system and other miscellaneous squeals and rattles. For this reason 0.5 m is assigned as the height of this noise source above the railway track.

9.3 Whistle Noise

The final noise source that can be attributed to trains is the whistle. In general this is not a widespread problem; however locations near a road/rail crossing will be repeatedly exposed to this noise.

The whistle is usually sounded intermittently over a distance of 400 m up to the point for which an audible warning is required. Although the whistle is not usually sounded continuously, this model assumes for simplicity that it is. It is also assumed that half the trains during each 24-h period travel in each direction.* These two assumptions simplify the calculations, but the levels calculated at a given receiver position for a single train passby will be too high for a train whistling on the far side of the "crossing" and too low for a train whistling on the near side.

For a train travelling at S km/h, the A-weighted sound level at a distance of 15 m from the track is approximately:

$$0 \text{ dB for } t < -0.4/S$$

$$110 \text{ dB for } -0.4/S < t < 0.4/S$$

$$0 \text{ dB for } t > 0.4/S$$

where t = time in hours and the train passes the warning point at t = 0. The position of the train and hence the whistle relative to the crossing is given by 1000 St. The distance (p) from the whistle to the receiving point P shown in Figure 9.3 is then given by

$$p = \sqrt{D^2 + (1000(St) - X)^2}$$

The level measured at any instant at a point P is therefore:

$$\begin{aligned} L_p &= 110 + 30 \log (15/P) \\ &= 145 - 15 \log [D^2 + (1000\ St - X)^2] \qquad [9.9] \\ &\quad \text{for } -.4/S < t < .4/S \end{aligned}$$

This is calculated assuming a propagation law of 9 dB per distance doubling to allow for ground effect and other forms of excess attenuation. The 24-h equivalent level is easily obtained from:

$$L_{eq} = 10 \log \left[\frac{1}{24} \int_{-.4/S}^{.4/S} \frac{10^{14.5}\ dt}{(D^2 + (1000St - X)^2)^{3/2}} \right] \qquad [9.10]$$

which evaluates to

$$L_{eq} = 101 - 10 \log S + 10 \log\left[\frac{(400 - X)}{D^2\sqrt{D^2 + (400 - X)^2}} - \frac{(-X - 400)}{D^2\sqrt{D^2 + (-X - 400)^2}}\right]$$

[9.11]

*Principle of Conservation of Trains!

This result is for the passbys of two trains in opposite directions; the level due to N trains may be found by adding 10 log(n/2) to the result of Eq. 9.11.

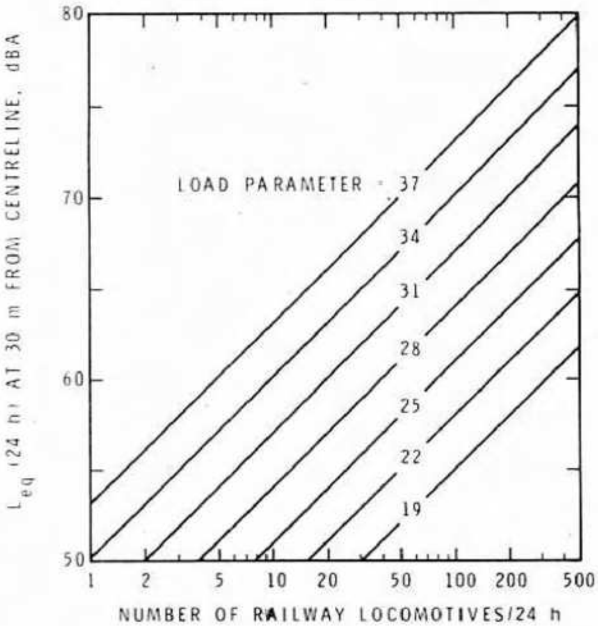


FIGURE 9.1

PREDICTED EQUIVALENT SOUND LEVEL FROM RAILWAY LOCOMOTIVES (L_{eq} (24 h)) AT 30 m FROM CENTRELINE (BEFORE CORRECTIONS)

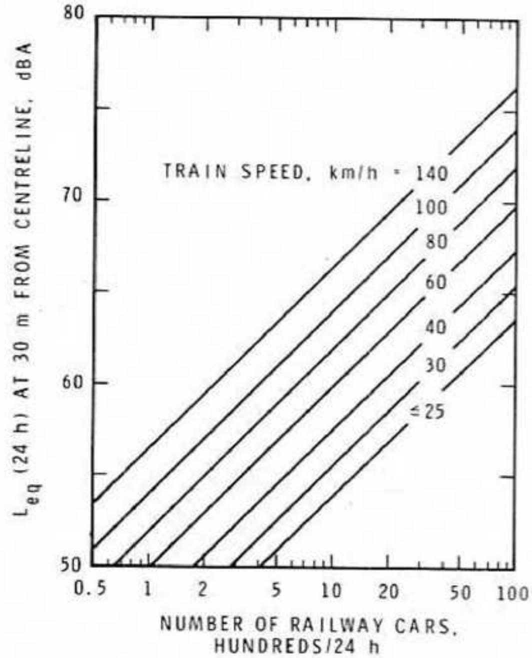


FIGURE 9.2

PREDICTED EQUIVALENT SOUND LEVEL FROM WHEEL - RAIL INTERACTION (L_{eq} (24 h)) AT 30 m. FROM CENTRELINE (BEFORE CORRECTIONS)

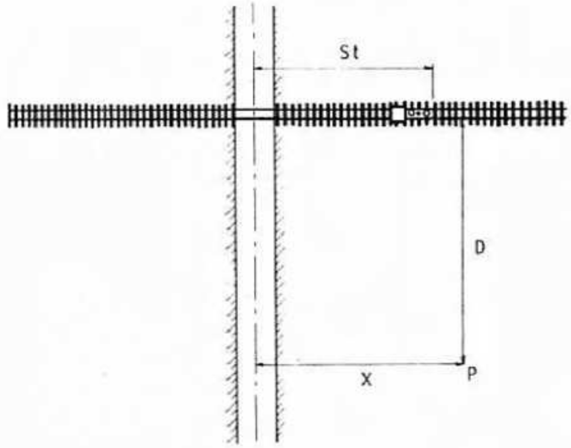


FIGURE 9.3

PARAMETERS USED TO CALCULATE SOUND LEVEL DUE TO TRAIN WHISTLE

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