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RESIDENTIAL PLANNING WITH RESPECT TO ROAD AND RAIL NOISE

by T.D. Northwood, J.D. Quirt and R.E. Halliwell

ANALYZED

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Les auteurs décrivent une façon d'assurer aux habitations une protection adequate contre les bruits de la circulation routière et ferroviaire. La méthode comprend trois étapes: 1) l'établissement de critères de bruit acceptables à l'intérieur d'un édifice et dans un espace abrité en plein air; 2) la prédiction des niveaux de bruit en un endroit donné, compte tenu de la densité de la circulation, des obstacles, des effect topographiques et de l'atténuation au sol; 3) la conception d'un édifice répondant aux critères de bruit.

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Residential Planning with Respect to Road and Rail Noise*

T. D. Northwood,† ** J. D. Quirt,† and **R. E. Halliwell†** describe a procedure for providing adequate protection to housing from the noises of road and rail traffic. The method involves the establishment of criteria of acceptable noise, inside a building and in a sheltered outdoor space; prediction of the noise level at a proposed site, considering traffic flow parameters, barriers, topographical effects, and ground attenuation; and the design of a building to meet the noise criteria.††

In planning residential development, one factor to consider is the potential exposure to high levels of noise from nearby roads or railways. This is an important concern to the eventual residents, and to the builders and regulatory agencies as well. One such agency is Central Mortgage and Housing Corporation, a Canadian government agency for funding housing construction. This article describes a guideline prepared for this corporation by the National Research Council of Canada (NRC).[1] The basic assignment was to produce a set of rules that could be used by the corporation and its clients to evaluate the noise at a proposed housing site and to make a decision regarding the suitability of the site. The decision might be that noise was not a significant problem, that the site was conditionally acceptable (with suitable noise control measures), or that the site was too noisy to be made acceptable for corporation lending purposes.

The guideline was originally prepared for use by nonexperts who may be unfamiliar not only with acoustical concepts, but also with any degree of mathematical complexity. The resulting document makes extensive use of tables, and requires only the ability to select the appropriate values from the tables, and then add or subtract these values as instructed. Although the format is easy to use, the document is rather bulky and obscures the physical significance of the various steps in the procedure. The physical significance will be emphasized here, although some tables from the original guideline are included to indicate the ease with which it can be used.

Although simplicity was a key principle, the document also aims at achieving its objective with reasonable precision and with a minimum of arbitrariness. As with any set of rules, there will be situations that do not fit exactly; the guideline provides the option for a developer or his acoustical consultant to propose another way of meeting the noise requirements.

It should be noted that since the planning document was adopted, in the spring of 1978, the various rules for predicting noise levels have been under continuing scrutiny as new data were collected. This article therefore reflects a number of minor changes made after the development was reported a year ago.

Noise Descriptors

The first step in the evolution of the project was to select a suitable measure of noise, considering both the fluctuating character of road and rail noise and subjective responses to

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TABLE I
Noise Descriptor Values for Various Idealized Sounds

	L_1	L_{10}	L_{50}	L_{eq}
Steady sound, 40 dB	40	40	40	40
Steady sound, 40 dB, except 80 dB 0.2 percent of time (3 min/24 h)	40	40	40	53
Steady sound, 40 dB, except 80 dB 2 percent of time (30 min/24 h)	80	40	40	63
Steady sound, 40 dB, except 80 dB 20 percent of time (5 h/ 24 h)	80	80	40	73
Steady sound, 80 dB 100 percent of time	80	80	80	80

such noises. It was assumed at the outset that the spectral content of the noises involved is adequately described by A-weighted levels. It should be pointed out, however, that the frequency spectrum of the noise undergoes several transformations between the source and the inside of a building, and this effect is not explicitly taken into account. Specifically, the low-frequency components of the noise are usually attenuated less than is indicated by the reduction in A-weighted level.

Generally, two aspects of fluctuating noises are likely to be significant: the total noise exposure (considering both average level and duration) and the maximum level. The total exposure is an indicator of the extent to which the noise may interfere with continuing activities such as listening to speech or music. Maximum levels may be associated with special distracting or disturbing effects; an important example is sleep interference, since even one brief noisy event may awaken a sleeper.

In the early stages of traffic noise research the most popular descriptors were the statistical measures (L_{10}, L_{50}, L_{90}, and so on), but none of these are particularly sensitive to peak events. Several derived quantities, such as the Traffic Noise Index and the Noise Pollution Level, take account of the *variability* of the noise, but not explicitly of the maximum levels involved. One approach considered was the use of two criteria: a statistical level (L_{10} or L_{50}) together with the level caused by some specified peak event, such as the passby of a noisy truck.

While these questions were being considered, the concept of an energy-equivalent average level L_{eq}, defined as the continuous steady level that would carry the same average energy over a given time interval T, was being developed in Europe and applied successfully to many noises, including road and rail noise. In its most common form,

$$L_{eq} = 10 \log\left\{(1/T) \int_0^T [p^2(t)/p_0{}^2]dt\right\}, \qquad (1)$$

where p is the instantaneous sound pressure and p_0 is the reference pressure of 20 μPa. Various averaging intervals, from one to twenty-four hours, may be used.

Since L_{eq} is simply related to the total sound energy in an interval, it is an easy matter to add up the contributions from several independent noise sources — not only from the individual vehicles on one road, but also from other roads and from railways and other noise emitters.

A characteristic of L_{eq} is that it is quite sensitive to occasional peak levels of a fluctuating sound, as well as a good indicator of total exposure. This aspect is illustrated in Table I, where values of L_{eq} and other descriptors are given for a few combinations of steady and peaked sounds. It will be seen that the statistical levels are insensitive to brief bursts of high level sounds. Even L_1, which is often interpreted as the maximum level, is unaffected until the duration of high level sound exceeds 15 minutes in 24 hours. In contrast, a 3-minute burst at high level (equivalent, say, to the passage of a garbage truck) raises the value of L_{eq}(24 h), in this example, by 13 dB.

Because much of the information on social response is expressed in terms of L_{eq}(24 h) — that is, the level averaged over 24 hours — this quantity was selected as the descriptor for the guideline. It also has the advantage that road traffic statistics for the 24-hour interval are more generally available.

Comparison of L_{eq}(24 h) and L_{dn}

As work proceeded on the NRC document, still another descriptor emerged. This is L_{dn}(day-night level), which is a modification of L_{eq} obtained by adding 10 dB to levels occurring between 10 PM and 7 AM. This is now coming into common use in the United States, and it was therefore carefully considered as an alternative to L_{eq}(24 h). It was noted, however, that although L_{dn} is intended to give extra weight to nighttime noise, the practical result is rather trivial. Fig. 1 shows the difference of $L_{dn} - L_{eq}$(24 h) plotted against L_{eq}(24 h) for data drawn from several sources, notably from Ref. 3. It will be seen that over a wide range of levels there is a consistent relation between the two quantities. The mean difference over the whole range is 3.0 dB, with a standard deviation of 1.4 dB. The regression line shows a slight slope, similar to that observed by Schultz in other traffic data, but over the range of concern in this project it is sufficient to assume a constant difference of 3 dB.[4] It appears, therefore, that shifting to L_{dn} merely changes all the numbers by 3 dB, and at the same time contaminates good physical data by mixing in an arbitrary adjustment term. It was concluded that L_{eq}(24 h) should be retained for the purposes of this project.

To provide some additional protection against sleep interference, the guideline simply specifies a noise limit for

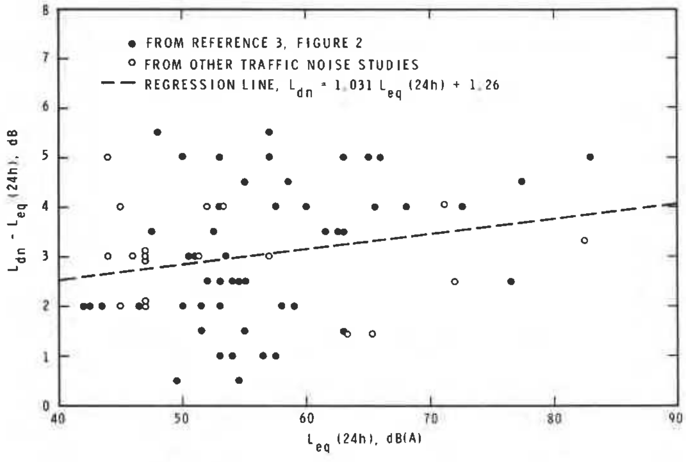

Figure 1 — Relation between L_{eq} (24 h) and L_{dn} for various noise sources

bedrooms that is 5 dB lower than for other living spaces. This approach has the added virtue of protecting shift workers (approximately 15 percent of the working population) and others who must sleep during the day, and who therefore would gain nothing from a nighttime penalty.[2] In addition, it encourages the designer to plan bedrooms on the most sheltered side of dwellings.

Subjective Responses to Fluctuating Noises

Other things being equal, one might expect that community reactions to noises would be similar regardless of the kinds of noise sources. Schultz, in an ambitious survey of social response studies, showed that several examples did fit a consistent pattern (Fig. 2).[4] This discovery required careful sifting and interpretation of data based on a variety of social survey techniques and physical descriptors.

Most of Schultz's clustering data were for aircraft noise. For the purposes of this study, it was of interest to examine specifically the responses to road noise. Some samples, including a few of Schultz's non-clustering data, are shown in Fig. 3. The lack of clustering in the case of road noise is exemplified by the two Swedish studies (curves 5 and 6): both are reasonably well documented and seem essentially similar in procedures, yet they differ by more than 10 dB in the noise level corresponding to a given percent of respondents said to be "very annoyed." The problems of characterizing noise exposure on the one hand and the degree of disturbance on the other are perhaps accentuated in the case of road traffic noise, which tends to constitute the all-pervasive background sound. It is an interesting topic that warrants detailed research. For present purposes, however, it must suffice to note that an outdoor level of 55 dB(A) is the threshold level at which significant annoyance begins.

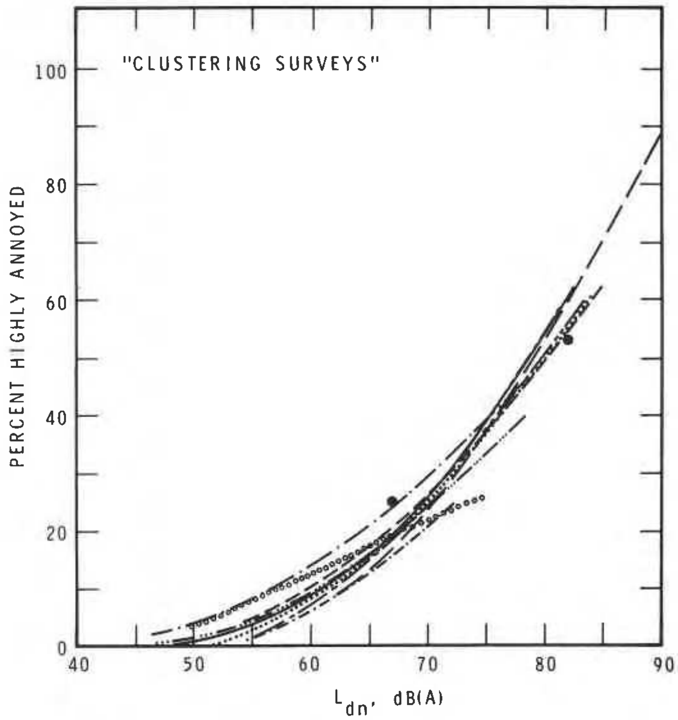

Figure 2 — Schultz's cluster of annoyance data from twelve surveys[4]

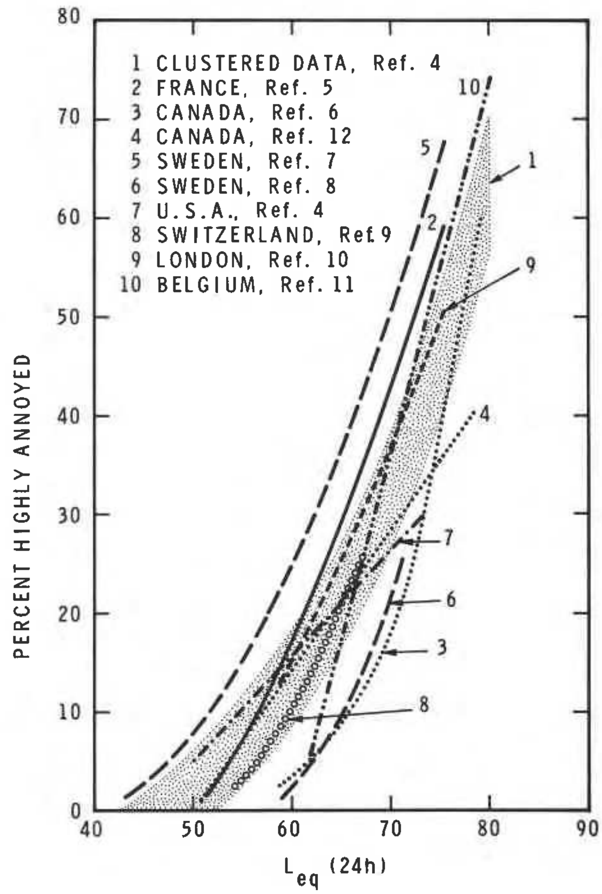

Figure 3 — Annoyance versus street traffic noise; a compilation of social survey data

Noise Criteria

From the results of social surveys shown in Fig. 3, it is observed that the percentage of people annoyed by outdoor noise increases sharply when L_{eq} (24 h) *outside* dwellings exceeds about 55 dB(A). Careful study of the response data (see, for example, Ref. 7) makes it apparent that this response is usually based on how the noise affects *indoor* activities. For typical uninsulated dwellings with openable windows, a 55 dB(A) outdoor level would correspond to 40 to 45 dB(A) indoors. This is indeed the threshold level above which one could expect interference with such indoor activities as listening to conversation or music. Sleep interference seems to be related more directly to peak events that intrude above local internal background.[17,18] For this kind of problem an extra margin of protection appears necessary, although firm data are not easy to find.

If only indoor levels mattered, one could propose a simple increase in the sound insulation of dwellings so they could withstand any level of outdoor noise. Most planning authorities, however, feel that every dwelling should have a certain amount of habitable outdoor space, in the form of patios, balconies, or children's or adults' recreation grounds. An appropriate noise limit for such areas is about 55 dB(A), which permits communication in a slightly raised voice.

If the noise exposure at a given site is no more than 55 dB(A), then for purposes of the guideline the site is considered acceptable without any special measures. When this level is exceeded, the outdoor amenity requirement may be met by locating such spaces on the quiet side of buildings or assuring that they are otherwise screened from the noise source. It is estimated that the maximum attenuation obtainable by screening is about 20 dB. Hence, the practical limit for dwelling purposes is an outdoor level of about 75 dB(A) on the exposed side of the building. For the region between 55 and 75 dB(A), special screening and sound insulation procedures are specified to achieve acceptable outdoor and indoor climates.

Finally, it is of interest to compare these requirements with those of other housing or planning authorities. Such comparisons are not always easy, since almost every authority has its own noise descriptors and its own way of setting requirements, but a selection of such requirements together with the NRC criteria, is shown in Table II.

TABLE II
MAXIMUM LEVELS RECOMMENDED BY VARIOUS AUTHORITIES*

Authority	Outdoors	Indoors
Wilson report, 1963 (Ref. 13)		(L_{10})
Suburban		Day, 45; night, 35
Busy urban		Day, 50; night, 35
Sweden — National Board of Urban Planning (Ref. 14)		
Inhabited rooms	$L_d = 55$	$L_d = 35$, $L_n = 25$
Outdoor recreation areas		
Commins and Meir (Ref. 15)		$L_d = 40$, $L_n = 35$
European community commission (1976)		L_{eq} (24) = 39, $L_{dn} = 43$
US EPA — Guidelines for preparing environmental impact statements on noise, 1977 (Ref. 16)	$L_{dn} = 55$	($L_{dn} \simeq 40$ dB with windows open)
NRC model (present paper and Ref. 1)	Recreation area	L_{eq} (24 h)
		Bedrooms 35
	L_{eq} (24 h) = 55	Living rooms, Dining rooms 40
		Kitchens, Bathrooms 45

*Values in the table are A-weighted sound pressure levels in decibels

Characteristics of Road Traffic Noise

The noise prediction model devised here of course draws on the data and ideas of other groups, but most particularly on a model developed in Sweden.[19] Several of their concepts, though with some modifications, will be recognized here.

The main factors that govern the noise generated by road traffic include the number of vehicles per day, traffic speed, fraction of heavy vehicles, road gradient, nearby stops, and the type and condition of the road surface. In formulating a mathematical model, the most obvious starting point is the noise emitted by typical individual vehicles. For simplicity, the NRC 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 Fig. 4, is based on a synthesis of our experimental results and data from the literature.[20-23] The maximum passby noise from light vehicles is assumed to increase at 10.5 dB per doubling of speed. (Observed values range from approximately 9 dB to 12 dB.[22,23]) Truck noise varies more slowly at low speeds (where it is dominated by engine noise), but at higher speeds the tire noise is more significant, and the dependence on speed should be similar to that for cars. This relationship between the two classes of vehicles at a given speed was handled by treating each heavy vehicle as equivalent to h light vehicles, where h is given by

$$h = \text{antilog}_{10}\ (H/10) \qquad (2)$$

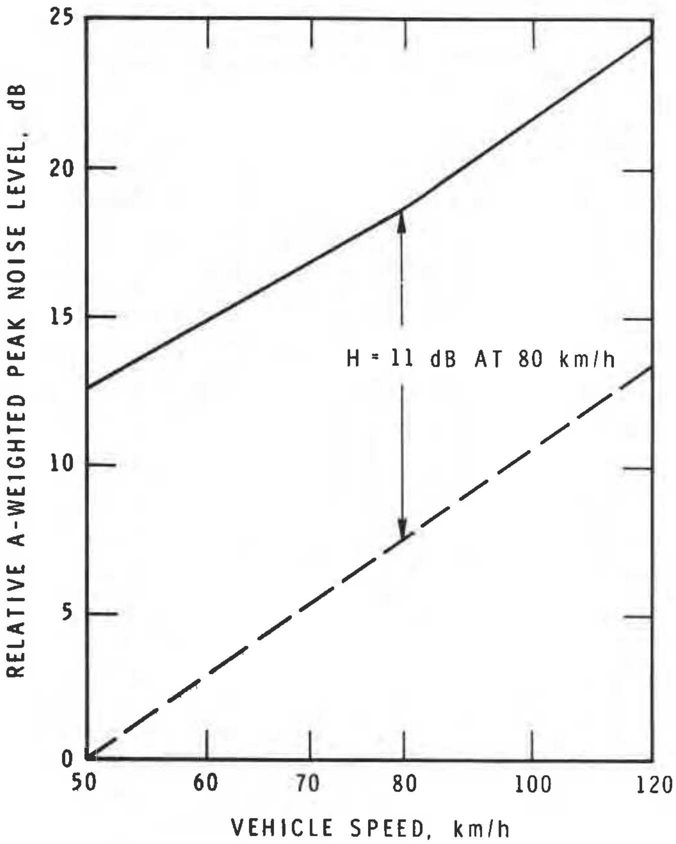

Figure 4 — Assumed relative peak noise levels for individual vehicle passbys. The solid line and dashed line represent the peak levels for heavy vehicles and light vehicles, respectively.

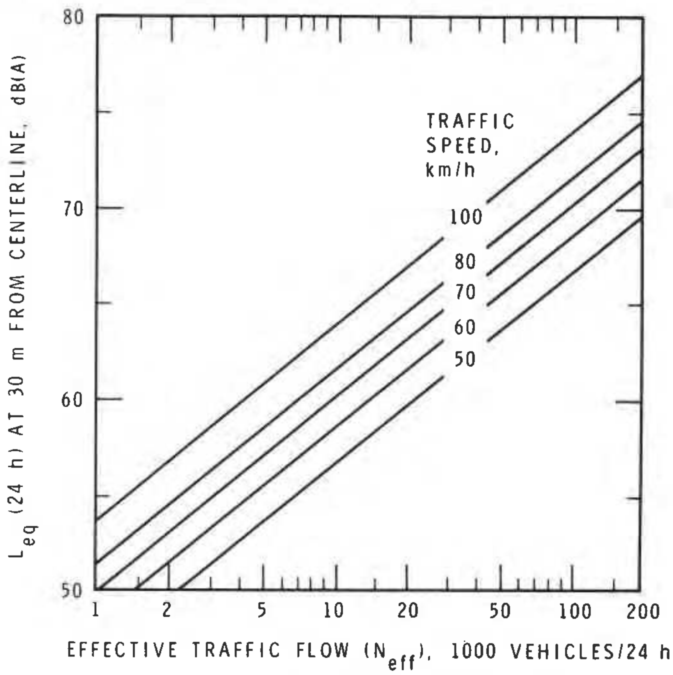

Figure 5 — Predicted equivalent sound level L_{eq} (24 h) at 30 m from the centerline (before corrections)

TABLE III
Abbreviated Example of Noise Source Tables in Ref. 1*

Daily Volume (Vehicles/24 h)	% Heavy Vehicles 0	1.5	3	5	8 · · ·	80	100
1,000	49	50	51	52	53	61	62
1,250	50	51	52	53	54	62	63
1,600	51	52	53	54	55	63	64
2,000	52	53	53	55	56	64	65
2,500	53	54	55	56	57	65	66
3,150	54	55	56	57	58	66	67
⋮							
250,000	73	74	75	76	77	85	86

*Values in the body of the table are L_{eq} at 30 m from centerline; posted speed 50 km/h. Each table is the equivalent of one of the curves in Fig. 5

and H is the difference in decibels between the curves in Fig. 4. The value of h is then used to calculate the effective traffic volume (N_{eff}) from the expression

$$N_{eff} = N_{light} + hN_{heavy}, \qquad (3)$$

where N_{light} and N_{heavy} are the number of light and heavy vehicles per day, respectively. This may in turn be used in Eq. 4 to obtain the predicted equivalent sound level at 30 m from the centerline:

$$L_{eq} = 25 \log_{10}(S) + 10 \log_{10}(N_{eff}) - R, \qquad (4)$$

where S is the traffic speed in kilometres per hour and R is a parameter used to fit Eq. 4 to actual roadside measurements. The noise produced by a given traffic flow may vary considerably, depending on the type of road surface and its condition.[21] However, because this feature is likely to change at a given site over a period of years, a single "typical" value, R = 26 dB, was used in the model. The variation in actual road surfaces will presumably be one source of scatter in the relationship between measured and predicted noise levels.

The curves in Fig. 5 present the levels predicted using the typical value of R in Eq. 4, for common traffic speeds; these curves are applicable in the absence of barriers or wind and ground attenuation, and assume free-flowing traffic on a level road. In the simplified version of the model, the predicted source noise level can be obtained directly from tables similar to Table III.[1] Corrections for

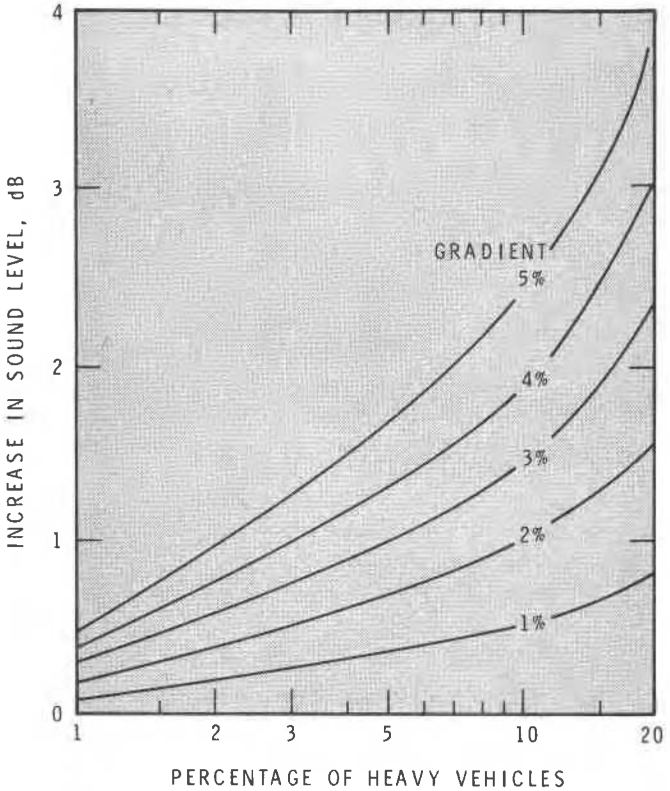

Figure 6 — Correction to predicted L_{eq} (24 h) to allow for road gradients

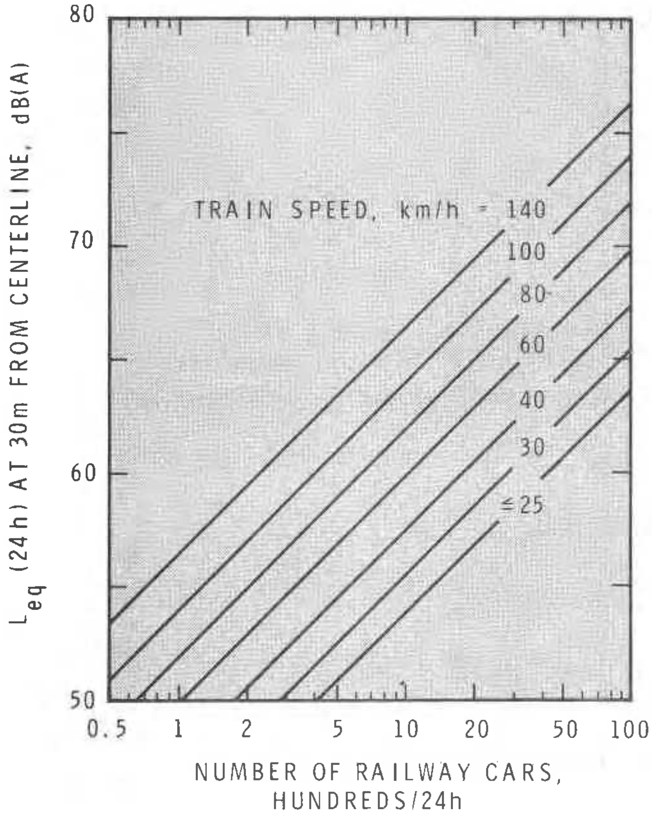

Figure 8 — Predicted equivalent sound level from wheel-rail interaction; L_{eq} (24 h) at 30 m from centerline, before corrections

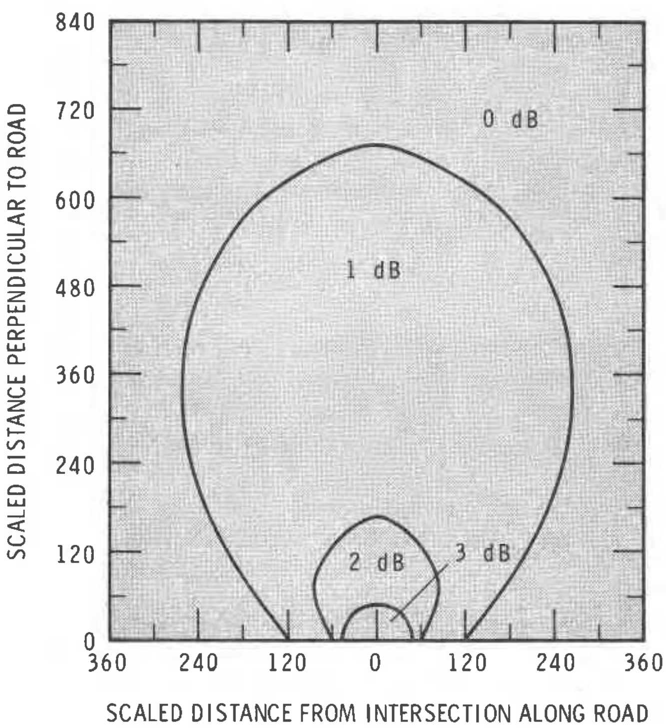

Figure 7 — Correction to predicted L_{eq} (24 h) to allow for nearby stops

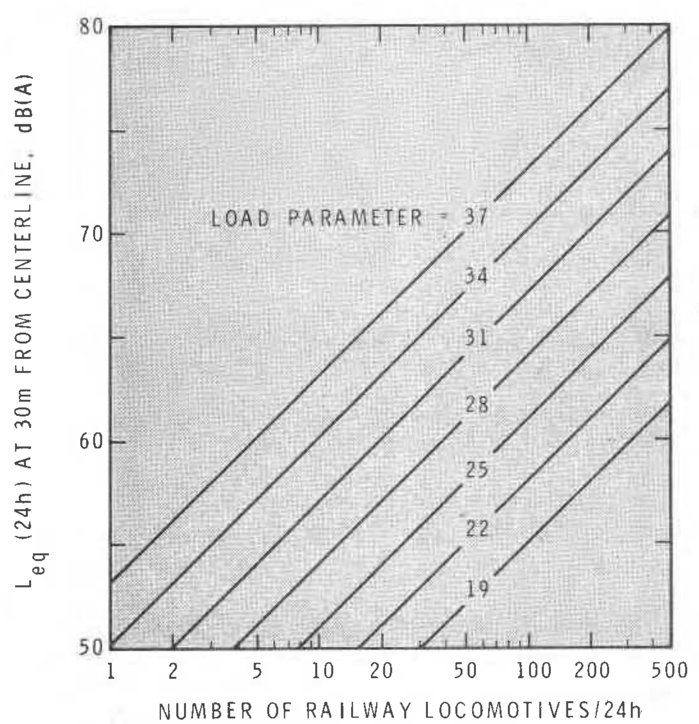

Figure 9 — Predicted equivalent sound level from railway locomotives; L_{eq} (24 h) at 30 m from centerline, before corrections

gradients and nearby stops are given in Figs. 6 and 7. These are based on Refs. 19, 21, and 25, as discussed in Ref. 24.

Noise Levels Due to Railway Traffic

Railway traffic differs from road traffic in that it is composed of a relatively small number of discrete events. Hence, a more deterministic method of description is used. Noise from the wheel-rail interaction and from the locomotives are considered separately, and the resulting noise levels at the proposed building site are then combined by power summing.

Source data required for a typical 24-hour period are the total number of railway cars, the total number of locomotives, and the nominal train speed. In cases where several distinct classes of trains are involved or where there are several tracks, the parameters for each should be obtained and the associated values of L_{eq} (24 h) calculated separately.

The wheel-rail noise at 30 m as a function of the number of railway cars per 24 hours is given in Fig. 8 for a range of train speeds.[24] This graph is applicable to typical jointed rails in good condition; for continuous welded rails, the predicted values should be decreased by 3 dB. For propagation purposes, the noise source is assumed to be 0.5 m above the track.

Locomotive noise depends not only on the train speed, but also on the number of cars per locomotive.[24] In Fig. 9 the equivalent sound level at 30 m is given as a function of the number of locomotives per day, for several values of the load parameter. This parameter may be calculated as follows:

$$\text{load parameter} = 0.15\ C + 13.5 \log S, \qquad (5)$$

where C is the average number of railway cars per locomotive and S is the train speed in kilometres per hour. Locomotive noise is taken to be at a source height of 4 m above the track.

These procedures will not give valid results in special cases such as switching yards, tight radius curves (radius less than 200 m), or a railway elevated on a trestle. The special cases may differ markedly from the predictions of this simplified model, and should therefore be individually assessed, preferably including measurement at the site.

Noise Propagation

The procedures in the two preceding sections give the noise level at a reference distance of 30 m from the centerline of roadway or railway. To establish the noise level at the facades of a proposed building, a prediction model must provide corrections for the actual source-receiver distance, as well as any other features that would cause additional attenuation.

With a hard ground surface one would expect the decrease in the sound level to be 3 dB per doubling of distance typical of a line source. If, however, the surface between the road and the building site is covered with grass or other plants, there is an additional source of noise reduction, commonly called ground attenuation. A detailed evaluation of this effect requires knowledge of the acoustical impedence of the surface and complex calculations that would be out of place in a simple design guide such as this.[26] It is possible, however, to include some of the relevant physical parameters in a simple empirical model.

For a noise source very close to a flat grassy surface, the excess reduction in A-weighted sound level caused by the ground effect has the general form shown in Fig. 10. For receiver heights more than about 1 m above the surface, the ground attenuation depends primarily on the angle of propagation. For propagation very near grazing incidence, the attenuation is limited because of the effect of so-called ground or surface waves.[26]

Raising the source appreciably above the surface or other changes that raise the propagation path also reduce the ground attenuation; this was dealt with in this model by the concept of an "effective total height" equal to the sum of source and receiver heights.[19,26] As illustrated in Fig. 11a, 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. 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 source to receiver. A marked reduction in ground attenuation is also to be expected if a barrier or other obstruction interferes with the sound waves reflected from the surface. This can also be treated by using an extension of the effective height concept (Fig. 11b). The resulting effective total height and the horizontal source-receiver distance can then be used to obtain the ground attenuation from Fig. 12.

Obviously, this scheme for predicting ground attenuation requires knowledge of the source height — a need that is even more acute for predicting the effectiveness of barriers (as discussed later). A source height of 0.3 m was assumed for light vehicles, because the exhaust system, tires, and obvious reflecting surfaces are all close to the road surface. The situation is not as simple for heavy vehicles, whose major noise sources (tires, drive train, engine, exhaust stack) are all at different heights and vary in relative importance, depending on speed and other factors. For this model, they were treated as two sources: tire noise (0.3 m above the surface) and engine/exhaust noise (2.5 m above the surface). It was assumed that heavy vehicle noise is dominated by tire noise at 110 km/h (90 percent of total sound power) and that tire noise decreases by 12 dB per halving of the speed. For the curve in Fig. 4, this is equivalent to assuming that the engine noise is essentially independent of vehicle speed and dominates at low speeds. The equivalent source

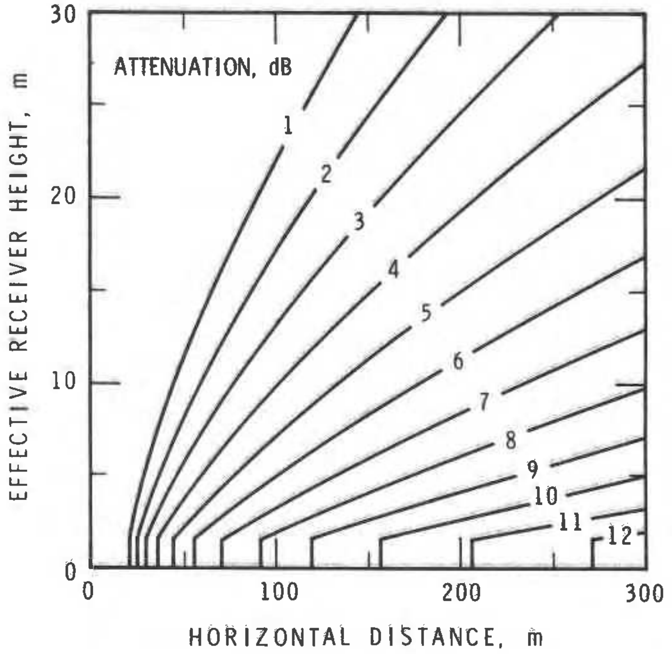

Figure 10 — Correction to predicted L_{eq} to allow for ground attenuation

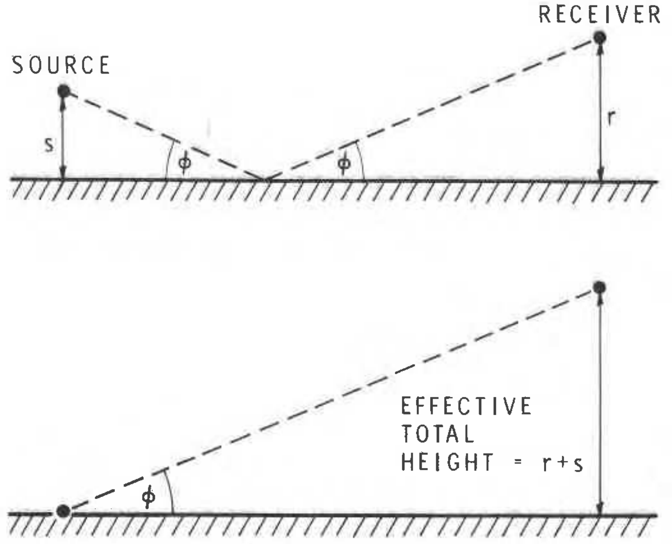

Figure 11a— Determination of effective total height for ground attenuation calculations

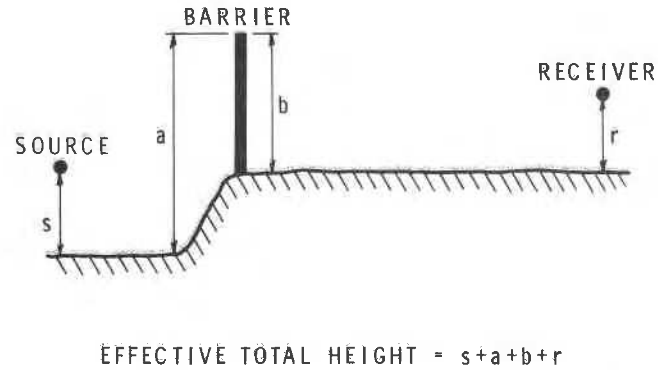

Figure 11b — Determination of effective total height for ground attenuation calculations when a barrier is involved

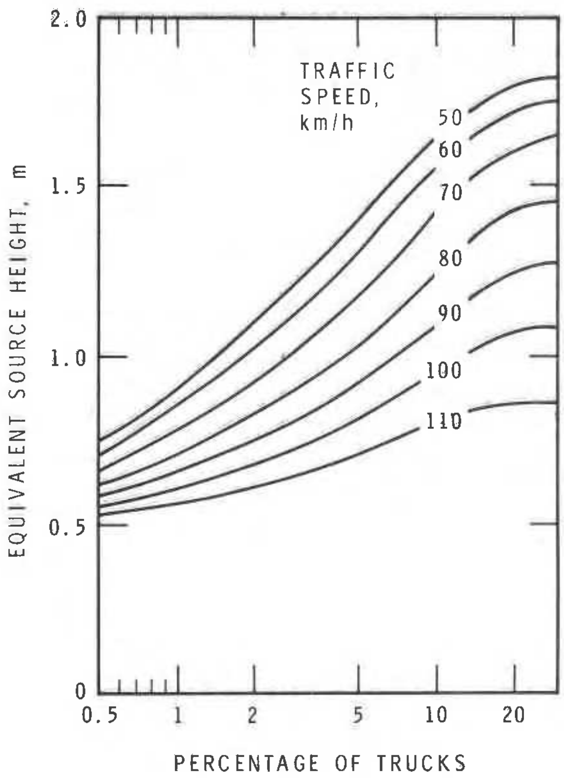

Figure 12 — Equivalent height of traffic noise source for various traffic flow conditions

heights shown in Fig. 12 were based on detailed calculations for a variety of barrier configurations with a range of relative strengths of the two noise sources.[24]

The predicted reduction in the A-weighted sound level provided by an infinitely long barrier is shown in Fig. 13, together with the well-known result derived by Kurze and Anderson.[27] This has been plotted with a split scale to provide reasonable resolution and to permit the inclusion of negative path length differences. The NRC model assumes a maximum barrier attenuation of 20 dB (for path length differences greater than 6 m) and lies slightly below the Kurze and Anderson result over the rest of its range. The resulting curve is deliberately made more conservative than the theoretical relation to provide some protection against effects not considered in the model, such as air turbulence and flanking paths associated with nearby reflecting surfaces.

In practice, the attenuation provided by a barrier is often limited by noise coming around one or both of its ends. After determining the barrier aspect ratio for each end of the barrier, as illustrated in Fig. 14a, the attenuation by a barrier of finite length may be obtained using the curves in

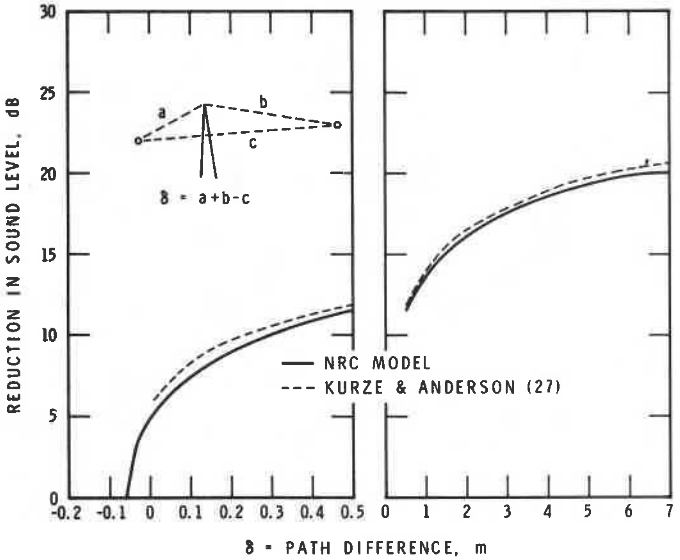

Figure 13 — Predicted reduction in L_{eq} provided by a barrier of infinite length. The reduction is a function of the path length difference δ (as illustrated in the inset sketch).

Fig. 14b. A first approximation is obtained by using the attenuation for an infinitely long barrier and the aspect ratio for the nearer end; this approximation and the aspect ratio for the other end are then used to obtain the final predicted attenuation. Linear interpolation between the curves should be employed when necessary. Strictly speaking, the contribution of flanking around the ends of a barrier is greater if the ground surface is acoustically hard than if there is appreciable ground attenuation. The curves in Fig. 14b are a compromise between the effects expected for a hard surface and those expected for a grass-covered surface. Because some of the relevant physical effects (such as ground attenuation and air absorption) depend on absolute distances rather than barrier geometry, this correction was derived by averaging the results for a range of typical spacings of source, barrier, and receiver.[24]

Building Design

The model can be used to predict the sound level at a building site. The presence of a building or a group of buildings on a site obviously complicates the picture, since some of the exterior walls will be at least partially shielded from the noise source. If there are no nearby reflecting surfaces, one would expect the sound power incident on the side walls to be 3 dB lower (because they are screened from half the road) and negligible incident sound power on the fully shielded rear wall.

The situation is substantially more complicated in a suburban environment, where adjacent buildings act as barriers and/or reflecting surfaces. For rows of detached housing, the guideline uses the simple rule that the incident sound levels at the side walls and at the rear wall are lower than the level at the directly exposed front facade by 3 dB and 15 dB, respectively. Some variation in this relationship would be expected, depending on the shape, orientation, and relative spacing of the buildings involved, and further complicated by scattering and absorption. A detailed evaluation of these effects is beyond the scope of this model, but the basic rules are found to provide a reasonable estimate.

In cases involving row housing or large apartment blocks, it is generally advisable to calculate the sound reaching the nominally sheltered facade via any obvious reflecting surfaces. This may be done by using the procedures already presented, with two modifications. The horizontal distance between the receiver and the image source is taken to be the sum of the distance from the source to the reflecting surface plus the distance from that surface to the receiver. Because the reflecting surface provides only a partial image of the original source, the sound level should be corrected by adding $10 \log_{10} (\alpha/180)$, where α is the angle (in degrees) that the reflecting surface subtends at the receiving point.

Having established the incident sound level at each facade, the next step of the design process is to select elements for the building's exterior facades that will meet indoor noise criteria. For this guideline and its companion document for insulation against aircraft noise, an index called the Acoustic Insulation Factor (AIF) was introduced for rating the sound insulation provided by various components.[28] To minimize the acoustical concepts required for the guideline, allowance is made for the absorption and component area by assigning to each construction a series of AIF values for various ratios of component area to floor area, rather than a single sound insulation rating. This form of presentation is readily accepted by architects because requirements for light and ventilation are commonly expressed in terms of the ratio of window area to room floor area. The AIF values in the tables are calculated for a room absorption in metric sabins equal to 80 percent of the floor area in square metres; this corresponds to a reverberation time of 0.5 s, which is typical for moderately furnished bedrooms or living rooms.

The difference between the indoor and outdoor A-weighted sound levels depends on the combined sound power transmitted by all components. In the case of a room envelope with n components, the design approach requires that no component should transmit more than $1/n$ of the total sound power that would give the desired indoor A-weighted level. Although in principle one could compensate for the low AIF of one component by a superior value for another, the lower one always dominates. Therefore, the equal power concept applied here is seldom conservative by more than one or two decibels. The AIF required for each component to meet the indoor L_{eq} criterion may be determined from the equation

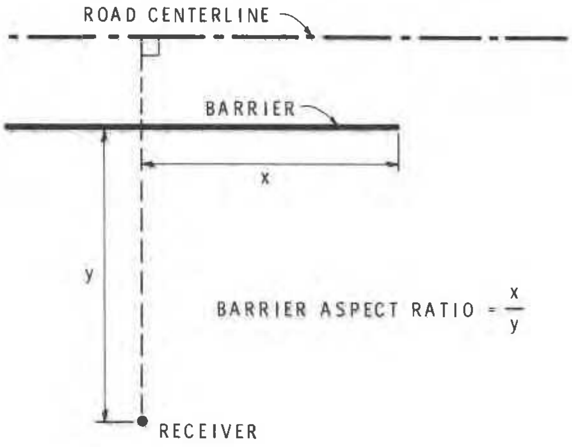

Figure 14a — Determination of the barrier aspect ratio for one end of a barrier

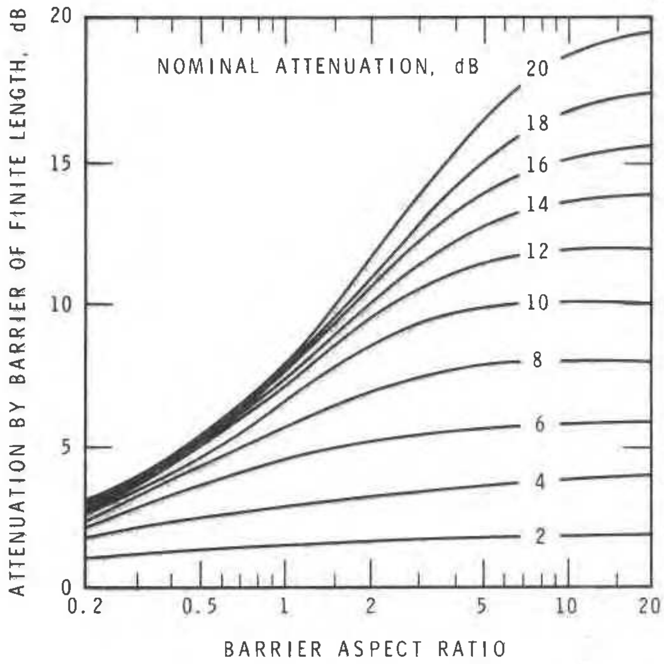

Figure 14b — Correction to the barrier attenuation to allow for sound coming around an end

TABLE IV

Acoustic Insulation Factor (AIF) for Various Types of Exterior Wall (From Ref. 28)

	Percentage of Exterior Wall Area to Total Floor Area of Room											Type of Exterior Wall
	16	20	25	32	40	50	63	80	100	125	160	
Acoustic Insulation Factor	45	44	43	42	41	40	39	38	37	36	35	EW1
	46	45	44	43	42	41	40	39	38	37	36	EW2
	47	46	45	44	43	42	41	40	39	38	37	EW3
	48	47	46	45	44	43	42	41	40	39	38	EW4
	55	54	53	52	51	50	49	48	47	46	45	EW5 or EW1R
	56	55	54	53	52	51	50	49	48	47	46	EW2R or EW3R
	57	56	55	54	53	52	51	50	49	48	47	EW4R
	58	57	56	55	54	53	52	51	50	49	48	EW6
	59	58	57	56	55	54	53	52	51	50	49	EW7
	61	60	59	58	57	56	55	54	53	52	51	EW5R
	63	62	61	60	59	58	57	56	55	54	53	EW8 or EW6R
	64	63	62	61	60	59	58	57	56	55	54	EW7R

Note: Where the calculated percentage wall area is not presented as a column heading, the nearest percentage column in the table should be used.
Source: National Research Council, Ottawa, November 1976.
Explanatory Notes:

1. EW1 denotes exterior wall as in Note 2, plus sheathing, plus wood siding or metal siding and fiber backer board.
   EW2 denotes exterior wall as in Note 2, plus rigid insulation (25 to 50 mm), and wood siding or metal siding and fiber backer board.
   EW3 denotes simulated mansard with structure as in Note 2, plus sheathing, 38 x 89 mm framing, sheathing, and asphalt roofing material.
   EW4 denotes exterior wall as in Note 2, plus sheathing and 20 mm stucco.
   EW5 denotes exterior wall as in Note 2, plus sheathing, 25 mm air space, 100 mm brick veneer.
   EW6 denotes exterior wall composed of 12.7 mm gypsum board, rigid insulation (25 to 50 mm), 100 mm back-up block, 100 mm face brick.
   EW7 denotes exterior wall composed of 12.7 mm gypsum board, rigid insulation (25 to 50 mm), 140 mm back-up block, 100 mm face brick.
   EW8 denotes exterior wall composed of 12.7 mm gypsum board, rigid insulation (25 to 50 mm), 200 mm concrete.
2. The common structure of walls EW1 to EW5 is composed of 12.7 mm gypsum board, vapor barrier, 38 x 89 mm studs, and 50 mm (or thicker) mineral wool or fiberglass batts.
3. R signifies the mounting of the interior gypsum board on resilient clips.
4. An exterior wall conforming to rainscreen design principles and composed of 12.7 mm gypsum board, 100 mm concrete block, rigid insulation (25 to 50 mm), 25 mm air space, and 100 mm brick veneer has the same AIF as EW5.
5. An exterior wall described in EW1 with the addition of rigid insulation (25 to 50 mm) between the sheathing and the external finish has the same AIF as EW3.

TABLE V
ACOUSTIC INSULATION FACTOR (AIF) FOR VARIOUS TYPES OF EXTERIOR DOORS (FROM REF. 28)

	Percentage of Total Door Area to Total Floor Area of Room									Exterior
	4	5	6.3	8	10	12.5	16	20	25	Door Type
Acoustic Insulation Factor	33	32	31	30	29	28	27	26	25	D1
	37	36	35	34	33	32	31	30	29	D2
	39	38	37	36	35	34	33	32	31	D3
	40	39	38	37	36	35	34	33	32	D4
	41	40	39	38	37	36	35	34	33	D5
	42	41	40	39	38	37	36	35	34	D1 — sd
	45	44	43	42	41	40	39	38	37	D2 — sd
	47	46	45	44	43	42	41	40	39	D3 — sd
	48	47	46	45	44	43	42	41	40	D4 — sd
	49	48	47	46	45	44	43	42	41	D5 — sd
	51	50	49	48	47	46	45	44	43	D3 — D3
	53	52	51	50	49	48	47	46	45	D5 — D5

Note: Where the calculated percentage door area is not presented as a column heading, the nearest percentage column in the table should be used.
Source: National Research Council, Ottawa, November 1976.
Explanatory Notes:
1. All prime doors must be fully weatherstripped.
2. D1 denotes 44 mm hollow core wood door (up to 10% of area glazed).
D2 denotes 44 mm fiberglass reinforced plastic door with foam or fiberglass insulated core (up to 5% of area glazed).
D3 denotes 35 mm in solid slab wood door.
D4 denotes 44 mm steel door with foam or fiberglass insulated core.
D5 denotes 44 mm solid slab door.
3. Except as noted specifically above, doors shall not have inset glazing.
4. sd denotes storm door. The AIF values apply when the glazed sections are closed.

$$\text{required AIF} = L_{eq}\,(\text{outside}) - L_{eq}\,(\text{inside}) + 10 \log_{10}(n) + B, \quad (6)$$

where n is the number of components in the exterior envelope of the room in question. One window, or several similar windows in a given wall, would be considered as one component, and the total window area would be used as the component area for the AIF. If a room has more than one exterior wall, it is necessary to consider each wall separately in order to take account of the different values of L_{eq} (outside); hence, greater sound insulation is required for the facades exposed to higher noise levels.

The term + B in Eq. 6 is present to permit use of the same AIF tables for insulation against road noise or aircraft noise.[1,28] The value $B = 2$ is used for the road noise version and $B = 0$ is used for aircraft noise, to allow for differences in the spectral balance of the noise source.

After determining the required AIF from Eq. 6, the designer selects appropriate components from Tables IV, V, and VI, which are taken from the metric versions of Refs. 1 and 28. For example, consider a bedroom (25 m^2 floor area) with one facade (15 m^2 wall area) exposed to traffic noise of 70 dB(A) and a second facade (10 m^2 total area including a window of 2 m^2) exposed to 67 dB(A). The total number of components is $n = 3$ (wall 1, wall 2, window). Following the fifth item of Table II, the required indoor level would be 35 dB(A). For the first wall, the required AIF is 70 – 35 + 10 log (3) + 2 = 42. Given that the wall area is 60 percent of the floor area, the appropriate construction (EW4) may be selected from Table IV. The other wall and the window must have AIF = 67 – 35 + 10 log (3) + 2 = 40 or greater. For the applicable column of Table IV (wall area = 32 percent of floor area), all the listed wall constructions provide greater sound attenuation than is required. The window (8 percent of floor area, AIF = 40) could be a double window of type W1-W1, with 66 to 90 mm spacing between the panes.

If for nonacoustic reasons a component is chosen whose AIF exceeds the requirement by 10 dB or more, it need not be counted as one of the room's components, and the required AIF for the other components is reduced. For the road noise, only three types of components were considered to be relevant: exterior doors, windows, and exterior walls. Roof-ceiling systems were ignored because most roof constructions used in Canada have AIF ratings that significantly exceed the requirements for sites where L_{eq} (outside) is less than 75 dB(A).

Summary

This article has described the form and evolution of a procedure for taking account of road and rail noise in residential planning. The procedure is designed to be relatively simple and practical, so that it can be used by nonacousticians such as builders and building officials. Keeping the method simple has made it necessary to ignore some relevant physical effects, and an individual prediction may consequently deviate several decibels from

TABLE VI
Acoustic Insulation Factor (AIF) for Various Types of Windows (From Ref. 28)

	Percentage of Window Area to Total Floor Area of Room												Type of Window: Single Glazing or Factory-Sealed Double Glazing	Double Window with Indicated Space Between Glass in Millimetres			
	4	**5**	**6.3**	**8**	**10**	**12.5**	**16**	**20**	**25**	**32**	**40**	**50**		**20 to 40**	**41 to 65**	**66 to 90**	**91 up**
	35	34	33	32	31	30	29	28	27	26	25	24	W1				
	36	35	34	33	32	31	30	29	28	27	26	25	WT1				
	37	36	35	34	33	32	31	30	29	28	27	26	W2				
	38	37	36	35	34	33	32	31	30	29	28	27	WT2				
	40	39	38	37	36	35	34	33	32	31	30	29	W3 or W4	W1-W1			
	41	40	39	38	37	36	35	34	33	32	31	30	W5	W2-W2			
	42	41	40	39	38	37	36	35	34	33	32	31			W1-W1		
	43	42	41	40	39	38	37	36	35	34	33	32		W2-W3	W1-W2	W1-W1	
	44	43	42	41	40	39	38	37	36	35	34	33		W3-W3	W2-W2	W1-W2	
Acoustic Insulation Factor	45	44	43	42	41	40	39	38	37	36	35	34		W2-W5		W2-W2	W1-W1
	46	45	44	43	42	41	40	39	38	37	36	35	W6 (sealed)		W2-W3 or WT1-W1		W1-W2
	47	46	45	44	43	42	41	40	39	38	37	36			W3-W3	W2-W3	W2-W2
	48	47	46	45	44	43	42	41	40	39	38	37	W7 (sealed)		W5-W5	W3-W3 or W4-W4	
	49	48	47	46	45	44	43	42	41	40	39	38			WT2-W1	W5-W5	WT1-W1 or W2-W3
	50	49	48	47	46	45	44	43	42	41	40	39			WT1-W5	WT2-W1	W3-W3 or W4-W4
	51	50	49	48	47	46	45	44	43	42	41	40			W5-W6 or WT2-W5	WT1-W5	W5-W5 or WT2-W1
	52	51	50	49	48	47	46	45	44	43	42	41				WT2-W5	WT1-W5
	53	52	51	50	49	48	47	46	45	44	43	42					WT2-W5

Note: Where the calculated percentage window area is not presented as a column heading, the nearest percentage column in the table should be used.
Source: National Research Council, Ottawa, February 1977.
Explanatory Notes:
1. Glazing: 1 denotes 2 mm glass
   2 denotes 3 mm glass
   3 denotes 4 mm glass
   4 denotes 5 mm glass
   5 denotes 8 mm glass
   6 denotes 10 mm glass
   7 denotes 12 mm laminated glass
2. W denotes single glazed windows (e.g., W3 denotes a single pane of 4 mm glass).
   WT denotes factory-sealed double glazing with panes separated 19 mm or less (e.g., WT1 has two panes of 2 mm glass).
   W-W denotes double glazing (e.g., W2-W3 denotes double glazing with one pane of 3 mm glass and one pane of 4 mm glass with spacing between the panes as indicated at the top of the column).
   WT-W denotes factory-sealed double glazed unit plus storm window (e.g., WT1-W2 denotes a factory-sealed unit with two panes of 2 mm glass plus a storm window of 3 mm glass with space between as indicated at the top of the column).
3. Except as noted, data are for well-fitted weatherstripped openable units. The AIF applies only when all windows are closed.
4. Window types W6 and W7 are for fixed units sealed to the frame. For any other type of window fixed and sealed to the frame, add three (3) to the AIF given in the table.

a carefully measured result. Nevertheless, the average prediction for a large housing development should be close to reality, and on this basis it is considered to be a workable planning tool. The extent of deviations from the prediction model in typical road noise situations is being monitored in an ongoing measurement program.[29]

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