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A SCALE MODEL TECHNIQUE FOR INVESTIGATING TRAFFIC NOISE PROPAGATION

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A 30:1 scale model technique has been developed for investigating the propagation of noise from traffic on major roads and motorways. Validation studies have been carried out for a range of different road/housing configurations by comparing relative noise levels obtained using the model with field data obtained specifically for the purpose. This model has been used to obtain systematic prediction data and examples are shown for noise propagating from a road in a natural cut, noise penetration through a gap between adjacent blocks of houses, and containment effects associated with unbroken parallel building façades on opposite sides of the road.

1. INTRODUCTION

One of the environmental disadvantages of major roads is the noise arising from the vehicular traffic and such disbenefits can be minimized if reliable estimates of the noise field associated with any particular road configuration are available at the design stage. Direct measurements of noise levels associated with a range of existing roads can lead to empirical prediction curves, but such field studies are costly and time-consuming, are confounded with uncontrollable site factors and meteorological conditions, and must of necessity be limited to the range of configurations already employed by road designers.

Certainly a quantity of reliable field data is essential to establish the basic noise level produced by motor traffic and to determine its variation with traffic parameters. In this connection a coherent set of prediction equations based on regression analysis of field data has been established [1]. Once the basic noise level associated with any given traffic stream has been measured or predicted the problem reduces to that of predicting the way in which noise propagates away from the road. In the simplest cases such as noise barriers application of established physical principles or empirical results leads readily to solutions for the noise field. With more complex boundary conditions numerical methods can sometimes prove effective but techniques for solving problems in three dimensions are not yet sufficiently developed for such procedures to find general application. Thus it appeared worthwhile to examine the possibility of using scale models to evaluate noise propagation in the neighbourhood of motorways and as a means of investigating the role played by road configuration in modifying the spread of traffic noise.

A review of the published literature [2] showed that although models had been widely used in connection with the acoustics of enclosed spaces, their use for investigating the propagation of road traffic noise had not been fully exploited. Preliminary proposals for a more detailed evaluation were therefore outlined, the necessary facilities became available towards the end of 1970 and a preliminary report was published in 1972 [3]. At about the same time several other workers were also developing scale model techniques for investigating the propagation of traffic noise [4, 5] and in the years which have elapsed a considerable interest has been shown in application of the technique specifically to traffic noise propagation [6–8] and to other problems involving noise propagation [9–16]. However, the technique finally developed at NPL has several novel features, and the purpose of this paper is to outline the technique and to demonstrate its validity by showing comparisons between model data and the corresponding field values of L_{10}† for a range of different site configurations. The facility has also been used to evaluate more difficult road configurations for which systematic field data were not available. To illustrate the utility of the technique typical data are presented relating to noise propagating from a road in a natural cut, for noise penetration through a gap in between rows of houses, and for containment effects associated with unbroken parallel façades adjacent to a road.

2. DESCRIPTION OF MODEL

2.1. SCALING FACTOR

The minimum scaling factor which could be adopted was determined by the accommodation available, in this case an irregularly-shaped free-field room with free-space plan area approximately 5·9 m square. Since the objective was to use the model to investigate propa-

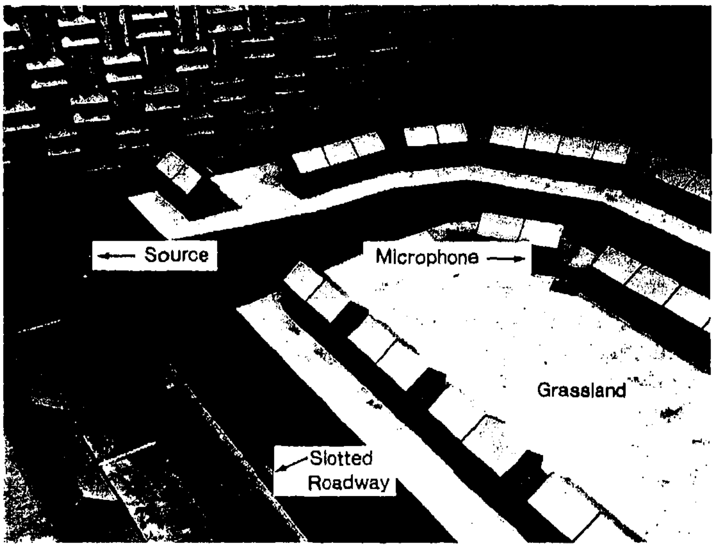

Figure 1. Model facility with typical road/housing configuration.

gation out to distances of 100 m from the road, a scale factor of at least 30:1 was indicated. On the other hand the noise spectrum must be scaled up in frequency by the same factor so, in order to minimize excess attenuation due to molecular absorption of sound in air and to allow the use of readily-available acoustical measuring equipment, it was desirable to adopt the lowest possible reduction factor. The scale factor finally adopted was 30:1 and the frequency range covered was 2 to 80 kHz; on full-scale this corresponds to approximately 63 to 2500 Hz and thus adequately covers the frequency range of importance for traffic noise studies. A photograph of the model with a typical test configuration is shown in Figure 1.

At the highest frequency, 80 kHz, under typical ambient conditions the attenuation of sound in air can reach 3 dB/m, which with allowance for the scaling factor would correspond to 100 dB/km on full scale, whereas the actual full-scale attenuation at the scaled frequency is an order of magnitude less than this [17]. Thus in reducing the model data it is essential to make correction for this disparity in attenuation rates, which becomes more important at

† L_{10} is the noise level in dB(A) exceeded for just 10% of the sample period.

greater distances from the roadway, and this was effected by using the on-line computing facilities described later. The frequencies of greatest significance in connection with traffic noise propagation are, when scaled, somewhat lower than 80 kHz so the correction procedure, although essential, is not critical in the vast majority of cases. Thus, although the attenuation of sound in air is known to be strongly dependent on temperature and humidity, it was not found necessary to take into account the day-to-day variation of the ambient conditions within the test chamber which typically were in the range 20 to 24°C and 40 to 60 % relative humidity. Over the frequency range 2 to 80 kHz an adequate approximation for the attenuation rate in dB/m at a frequency of f kHz was provided by the simple expression

$$\alpha = \exp\{3{\cdot}67 \log f - 5{\cdot}75\}.$$

For each individual source position this attenuation rate was multiplied by the slant distance from source to receiving microphone in order to obtain the correction to be applied to the recorded band level for each $\frac{1}{3}$-octave band. This procedure can only be approximate for it neglects the multiple reflection which sound undergoes in certain site configurations and this must be regarded as an inherent limitation of the model technique. In principle it could be overcome by diluting the air in the test chamber with a relatively non-absorbing gas but this was quite impracticable with the present facility. Moreover, there is no evidence that this neglect of the extra attenuation in cases of multiple reflection introduces significant error in any of the configurations investigated to date.

Nearly all the site configurations investigated exhibited symmetry about a horizontal line perpendicular to the road and whenever this occurred maximum use was made of the available area by modelling only little more than half the site. Nevertheless, with a 30:1 scale factor the available enclosure did not permit a sufficient length of road to be modelled for satisfactory data to be directly obtained out to the full distance of 100 m from the road. At this distance, for instance, the model road would need to be some 30 m long if the noise level from the source when at the end of its traverse were required to be 20 dB less than that at the distance of nearest approach. The length of model road actually available was a little under 5 m so that, in the absence of any additional attenuation due to ground absorption or shielding, a change of little more than 5 dB below peak level was achieved. Some account of the noise contribution from the lower flanks of the time/level history (which would have contributed had a longer roadway been available) was therefore taken by applying the inverse pressure/distance law to the flanks but this contribution was significant only at larger distances from the road and in no case was the correction a dominant factor for L_{10} prediction. Correction would, however, prove more important if the model were used to predict the whole time/level distribution as the effect on L_{50} and L_{90} is greater than the effect on L_{10}.

2.2. FREE FIELD ROOM FACILITY

The chamber available to house the model had previously formed part of a suite used for measuring sound transmission loss and is structurally completely isolated, with resilient mounts, from the main structure of the building. Although not essential, such isolation does yield an extremely low internal ambient noise level and with the high sound power output achieved from the noise source eliminated all spurious effects due to extraneous noise.

An essentially free field environment to house the model was achieved by completely lining the walls and ceiling of the enclosure with wedges made of sound absorbing material, leaving only the floor exposed. Design of the wedge unit presented no special problems. Good free field performance was required only above 2 kHz but to produce an enclosure with more general utility without materially reducing the working volume, an overall wedge length of 0·4 m was selected which functions well down to 500 Hz. The base of each wedge unit took the form of a cube with edge 0·2 m whilst the top portion comprised two integral tapered sections each with a vertex angle of 30°. The material used was Pritex NG22 flame-retardant polyurethane foam having a nominal bulk density of 25 kg m^{-3} and a specific flow resistance per unit length of approximately $1{\cdot}5 \times 10^4$ kg s^{-1} m^{-3}. Great care was taken to exclude from the free field enclosure all extraneous sound-reflecting objects as these are known to seriously degrade the performance, particularly at the high frequencies involved here. Thus no cables or power sockets were left exposed and illumination for the operators was provided by fluorescent lamps behind Perspex covers which were flush with and formed part of the false floor constituting the ground-plane.

Detailed samplings of the sound field due to a pure tone point source situated inside this enclosure when completely lined with these wedges have shown that for source/receiver separations of order 1 m the rms deviation from true inverse pressure/distance law for frequencies above 2 kHz is well under 0·2 dB [18]. Since the source used in the model studies produces a broad band noise spectrum rather than a pure tone, the resulting deviations in band levels will be even smaller than this. Certainly during the course of the model studies there was no evidence of measurable reflections from the walls of the chamber and it is concluded that any deficiencies due to non-ideal room performance are negligible.

2.3. NOISE SOURCE

Some model techniques have employed pulsed sound sources but if steady state propagation data are required these involve a complex analysis system. Thus in order to simplify the data handling a steady sound source was chosen. The requirement was for a compact omnidirectional sound source capable of producing a broad band noise spectrum covering the frequency range 2 to 80 kHz. The output level had to be such that when using a ¼ inch condenser microphone as the measuring device an adequate signal to noise ratio could be achieved out to the most distant regions of the model, even when the microphone was heavily screened by interposed obstructions. No electromagnetic or piezoelectric source meeting these requirements could be located and recourse was made to an air-jet device. A simple air jet requires such a large air flow to achieve adequate signal level in the required frequency range that extraneous effects due to air movement can intrude and similar drawbacks were found with crossed and opposing jets [19]. However, it was known that by making an air jet impinge on the edge of a sharp blade the noise level for a given air flow could be raised by some 30 dB, presumably due to vortex separation. Measurements showed that the noise spectrum could

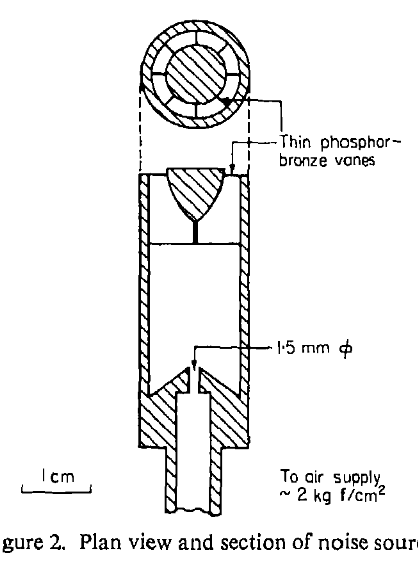

Figure 2. Plan view and section of noise source.

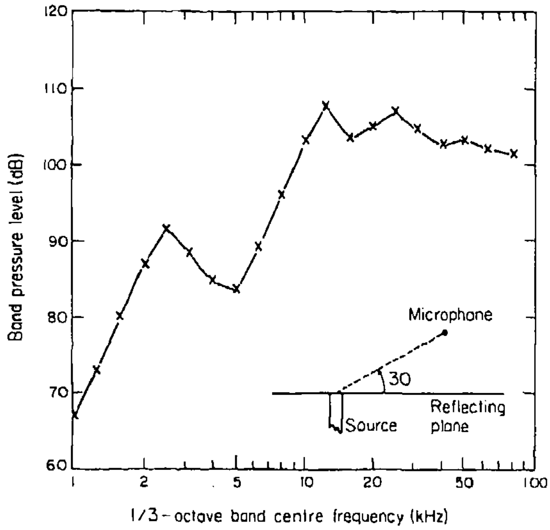

Figure 3. Spectrum of noise source measured at a distance of 0·35 m with the source flush with a plane; for model measurements this was electrically equalised to a typical A-weighted vehicle noise spectrum.

be varied to some extent by altering the separation between the blades and the jet. Moreover, containing the source in a tube, apart from proving experimentally convenient, also produced a useful increase in noise level at the low frequency end of the spectrum. Trial and error development led to the source design shown in Figure 2; the small conical insert at the open end of the tube, besides stabilizing the air flow, also improved the directional uniformity of the source so that the measured $\frac{1}{3}$-octave band pressure levels varied by less than ± 3 dB in the plane perpendicular to the tube axis and by less than ± 3 dB for all angles of elevation less than 30°. Over most of the frequency range the source directionality was significantly less than this and the equivalent (i.e., scaled) A-weighted noise level varied by only ± 1 dB(A).

The noise spectrum produced is shown in Figure 3 and it was found that the output was highly reproducible, the long term stability being better than 0·2 dB when operated from a compressed air supply via a commercial gas regulator valve at an outlet pressure of 2 kgf cm^{-2}.

2.4. SIMULATION OF BUILDINGS

Absorption data for typical facing brickwork indicate that the reverberation absorption coefficient varies from 0·02 at 125 Hz to 0·5 at 2 kHz [20]. Typical domestic windows act as panel resonators and enhance the absorption at low frequencies; actual values vary widely as they depend on window size and mounting but typical values of absorption coefficient range from 0·35 at 125 Hz to only 0·07 at 2 kHz [21]. With account taken of the greater area of brickwork generally found in traditional residential developments it is estimated that the average absorption coefficient is of order 0·1. However, it was established by model experiments that, at least for the site configurations investigated here, sound absorption at the façades of buildings was not the dominant loss mechanism so that precise simulation was not too important. This was indeed fortunate as it would probably have proved difficult to simulate the resonant absorption associated with the windows.

No convenient method for determining the absorption coefficient of materials up to 100 kHz was available but limited measurements in a conventional impedance tube indicated the normal incidence absorption coefficient of the rough side of 3 mm thick standard hardboard to be approximately 0·09 at 4 kHz (which on the full scale corresponds to approximately 125 Hz), increasing slowly with increasing frequency. This material was therefore used as a facing on the model buildings whilst the buildings themselves were constructed of 9 mm plywood.

For the predominantly suburban and urban sites investigated during the course of the validation studies, the buildings were mainly semi-detached or terraced two-storey buildings. The basic model building module comprised a unit 0·2 m long, 0·2 m wide, 0·24 m to the apex and 0·16 m to the eaves; two units were used to represent a pair of semi-detached houses whilst units were placed end to end for terraces. A number of garage units 0·17 m long, 0·09 m wide and 0·09 m high were also used and further basic units 0·25 m long, 0·2 m wide and 0·09 m high were available for constructing blocks of flats or offices. No attempt was made to reproduce small detail such as garden gates, fences, parked cars, trees or lamp-posts. However, it proved necessary to avoid the unrealistically prominent reflections at near grazing incidence which were found to occur when the façades of the model buildings were accurately aligned. Thus the front surfaces of adjacent units were slightly staggered and, where appropriate, the irregularities produced by bay windows and porches were simulated by using 20 mm × 50 mm battens extending to eaves height.

2.5. SIMULATION OF ROADS AND GROUND COVER

Road and pavement surfaces are generally good reflectors of sound and were simulated on the model by sheet aluminium or rigid plastic.

Excess attenuation associated with near grazing propagation of sound over absorbing ground has been widely reported and a theoretical explanation of the phenomenon has been established. Basically the sound wave reflected at the ground surface interferes with the wave propagating directly from the source to the receiver and causes a frequency-selective attenuation which depends on the height of the source and the receiver and on their separation. The magnitude of this excess attenuation also depends on the ground cover and direct field measurements of traffic noise propagating over standing corn showed that for a microphone height of 1·2 m L_{10} decreased at a rate of 6·6 dB(A) per doubling of distance, whilst over concrete little excess attenuation was detected and L_{10} decreased at a rate of 3·2 dB(A) per doubling of distance and was thus close to the value expected for a line source [22]. By far the most important case in practice is typical open grassland where the field measurements showed a rate of decrease of approximately 4·5 dB(A) per doubling of distance. It has also been shown [23] that corresponding values can be readily predicted theoretically on the assumption that ground behaves essentially as a homogeneous isotropic medium with a value of $(f/\sigma P)$ of 10^5 MKS units, where f is frequency (Hz), σ is the specific flow-resistance per unit thickness (kg s^{-1} m^{-3}) and P is the porosity (i.e., the contained air volume/total volume). Thus for model simulation where the frequency is scaled up 30 times it would be expected that the value of σP for the ground simulation material should be of order 3×10^6 kg s^{-1} m^{-3}. This suggested the use of one of the denser fibrous building boards; a range of fibre boards and similar materials were tested and it was concluded that the results for 11 mm thick Insulite softboard most nearly met the requirements although for practical reasons this material was covered with a coarse weave nylon cloth. Alternative methods of simulating ground cover have been reported in the literature [24, 25] but these do not appear to offer any significant advantages over the simple method used here.

2.6. MODE OF OPERATION

The mode of operation was as follows . A model of the required site was constructed, by using the prefabricated units and choosing the appropriate ground cover. A ¼ inch condenser microphone (Brüel and Kjaer type 4135) fitted with a nose-cone (type UA 0053) and a right-angle flexible adaptor was placed at the required measurement position. The subsequent signal channel consisted of a preamplifier (B & K type 2615) and thence via a 30 m extension cable to a measurement amplifier (B & K type 2607), a multi-filter (General Radio type 1925) and finally to a $\frac{1}{3}$-octave real time analyser (B & K type 5148) used in conjunction with a digital computer (Varian 620 L) having an 8 K store. Printed output was obtained via a Teletype machine and all programming was executed by using DAS assembler language. The parallel channel $\frac{1}{3}$-octave band multi-filter was used to adjust the frequency weighting to produce the required overall spectrum shape corresponding to a typical A-weighted vehicle noise spectrum, thus taking into account the frequency response of the complete measuring system and the output spectrum of the noise source. The digital recording system was triggered from a microswitch attached to the sledge which carried the moving source.

Before each run the overall noise level at a reference distance of 0·25 m from the source was checked to ensure source stability and the microphone co-ordinates were input. The source, mounted at a height of 17 mm and on a small sledge, was then slowly traversed along a narrow slot in the main road, by means of a wire and a small capstan mounted at one end of the road. The overall traverse length was 4·2 m and the traverse time was approximately two minutes. At intervals of 0·1 m, corresponding to 3 m on the full scale, a microswitch mounted on the source sledge was actuated and this triggered the digitizing equipment which recorded the instantaneous values of band level at the measurement position. Correction was then made for air attenuation as outlined in section 2.1 and the value corresponding to A-weighted noise level derived and stored. In this way a record was obtained of the A-weighted noise level corresponding to a single vehicle as a function of its position along the road.

Several different ways of using this information were investigated. Early attempts were directed towards producing a simplified direct reading method for obtaining relative noise levels over typical site configurations (for instance, in terms of the maximum noise level reached during the drive-by) but it was found that these simple measures did not correlate well with the field data. The simplest effective measure was to sum the total A-weighted energy recorded over the complete drive-by of the noise source and then, as shown in reference [3], the relative values of summated A-weighted energy did correlate fairly well with the corresponding field data. However, the availability of the on-line computing facility permitted a more sophisticated handling of the model data and this was used to obtain all the results presented in this paper. A typical traffic pattern having a Poisson distribution of vehicle spacing was generated and stored; the drive-by signature obtained with the single vehicle was then applied to each individual vehicle in the traffic stream and the resulting instantaneous A-weighted component noise levels at the measurement position summed to give the total instantaneous noise level. The traffic stream was then "moved" along the road by a distance corresponding to a $\frac{1}{2}$-second interval at a typical mean traffic speed and the noise level again computed. Proceeding in this way some five hundred values of instantaneous noise level at the measurement position were evaluated and from this distribution the noise level exceeded for 10% of the sample period was derived. For each measurement position printed output took the form of digital and graphical output of the 42 values of A-weighted noise level defining the single-vehicle drive-by and digital output of the derived value of L_{10}.

In general it was found that for any given site the relative values of L_{10} obtained from the model technique were almost independent of the vehicle spacing over the range encountered in practice (i.e., were almost independent of the equivalent traffic flow-rate and mean speed) and a typical flow-rate of 1700 veh/h at a mean speed of 75 km/h was adopted, leading to a mean vehicle spacing on the model of approximately 1·5 m. However, this mean vehicle spacing could be changed at run-time and in one case, where propagation along a narrow side-road was under investigation, it was found that the relative value of L_{10} did depend significantly on the mean vehicle spacing. Values close to those prevailing under the actual field conditions were therefore adopted in this case: i.e., a combined flow-rate of 2000 veh/h at a mean speed of 30 km/h, leading to a mean vehicle spacing on the model of approximately 0·33 m.

3. VALIDATION STUDIES

3.1. FIELD MEASUREMENTS

At the outset it was recognized that few systematic data were available against which to test the validity of the modelling technique. In particular, data were not available for propagation in typical urban and suburban areas where the complex fabric produces both multiple reflection and screening of the noise from road traffic. A series of field measurements was therefore undertaken to obtain detailed measurements covering a range of site configurations. Ten different well-defined sites were investigated and provided five sets of data relating to screening by typical two-storey houses essentially parallel to a main road, three sets relating to propagation along straight side-roads and one set relating to a curved side-road flanked by two-storey houses, and one set relating to each of the following: propagation over open grassland, screening by a continuous wall 2·3 m high parallel to a main road and the effect of a 6 m wide gap in a 2·5 m high barrier. In every case measurements were made under low-wind conditions at heights of 1·2 m and 4 m above ground, in the form of 10 minute noise samples which had been carefully edited to remove spurious events such as aircraft flyovers. In total some 287 noise measurements were taken and analysed statistically to derive corresponding values of L_{10}, L_{50} and L_{90}, and a detailed report on these measurements has been published [26]. A considerable quantity of additional data relating to a microphone height of 1·2 m above ground at three other predominantly open grassland sites alongside major roads and motorways was also available [22]. In evaluating the viability of the model technique the relative values of L_{10} only are used and it is convenient to consider three separate categories of sites: open grassland sites and sites with simple noise barriers, sites where screening is due predominantly to a row of houses situated parallel to a road, and side-road sites where a direct but angularly limited view of the traffic stream is maintained at all measurement points but including also one side-road site where there was in places only an indirect or reflected view of the traffic stream.

3.2. OPEN GRASSLAND SITES AND SIMPLE BARRIERS

Comparison of the open grassland field data with model results obtained for a single traffic stream centred on the nearside carriageway showed that the model tended to predict an attenuation rate which was more rapid than that found in the field. In this case it was therefore found necessary to repeat the model evaluation with the source moving in a slot centred on the far carriageway also, the final values for the variation of L_{10} with distance from the road being derived by combining the values obtained from the two source positions, through energy addition. As Figure 4 shows, for a typical microphone height of 1·2 m, field and model values of relative L_{10} are then in quite close agreement; for all open grassland data, some 85 measurements at four sites for microphone heights of 1·2 m and 4 m, the root mean square prediction error for the relative value of L_{10} was 1·77 dB(A). However, it should be noted that whenever significant screening was present between source and measuring microphone the use of combined data relating to the two opposing traffic streams did not lead to any improvement in correlation between field and model values of relative L_{10}. In all other cases the data reported here are therefore based on the single source traverse technique.

When modelling the barrier situations (2·3 m high continuous barrier and 2·5 m high barrier with single 6 m wide gap) exactly the same procedure was adopted as had been employed when obtaining the field data [26] and all levels behind the wall were expressed relative to the noise level recorded at the reference position 5·5 m from the nearside kerb.

For the above results combined, the agreement between relative values of L_{10} based on model studies and those actually measured in the field can be seen in Figure 5. The rms error is 1·72 dB(A) so that, if there is a Gaussian error distribution, 92 % of the predictions would be

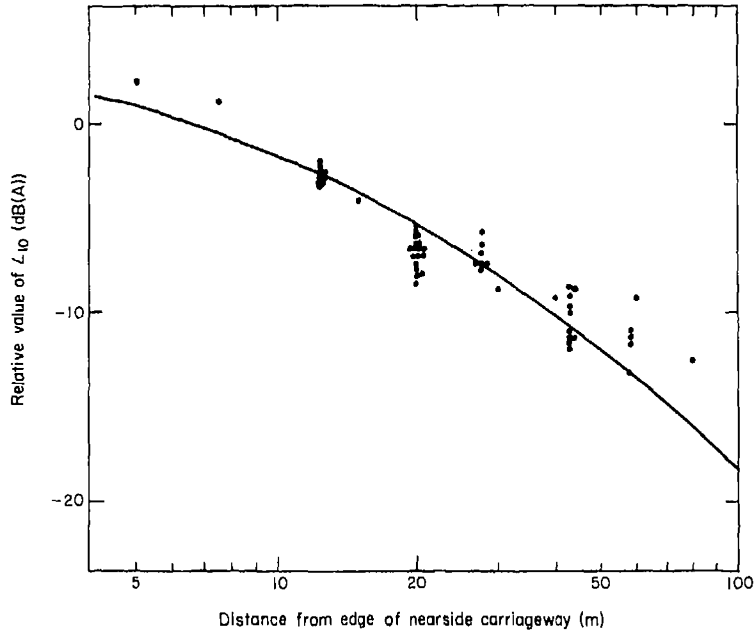

Figure 4. Comparison of field and scale model values of L_{10} for propagation over open grassland; microphone 1·2 m above ground. ——, Scale model result (two traffic streams); ●, experimental data for four sites.

expected to fall within ±3 dB(A) of the measured values and 99·6 % within ±5 dB(A). In fact there were twelve discrepancies larger than 3 dB(A) and only one in excess of 5 dB(A) out of the total of 107 results.

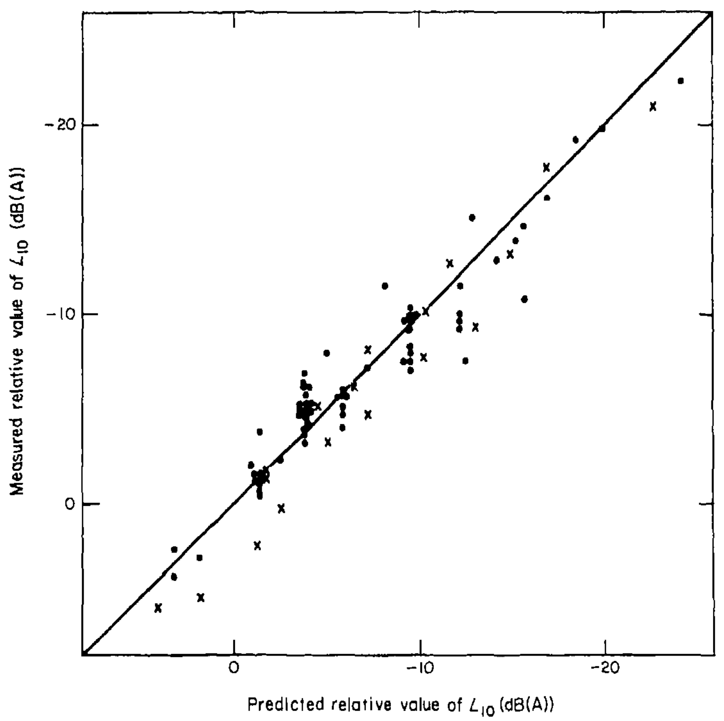

Figure 5. Prediction error for relative noise level for simple sites including open ground, a long noise barrier, and a barrier with gap. ●, Microphone 1·2 m high; ×, microphone 4 m high.

3.3. ROWS OF HOUSES PARALLEL TO THE ROAD

Results for the five different site configurations where two-storey semi-detached houses were essentially parallel to the road are compared in Figure 6. The overall rms error is 2·41 dB(A) with $N = 85$, whilst the mean error for a microphone height of 1·2 m is 1·3 dB(A) and for a height of 4 m is only 0·5 dB(A), with the model predicting too low an attenuation in both cases.

Now only the major features of the urban fabric were represented on the model (houses, garages, etc.) and no attempt was made to include specific features such as garden gates and fences, even though it was recognized that in some cases these have significant local effects. This procedure was adopted because the primary objective of the modelling technique was to

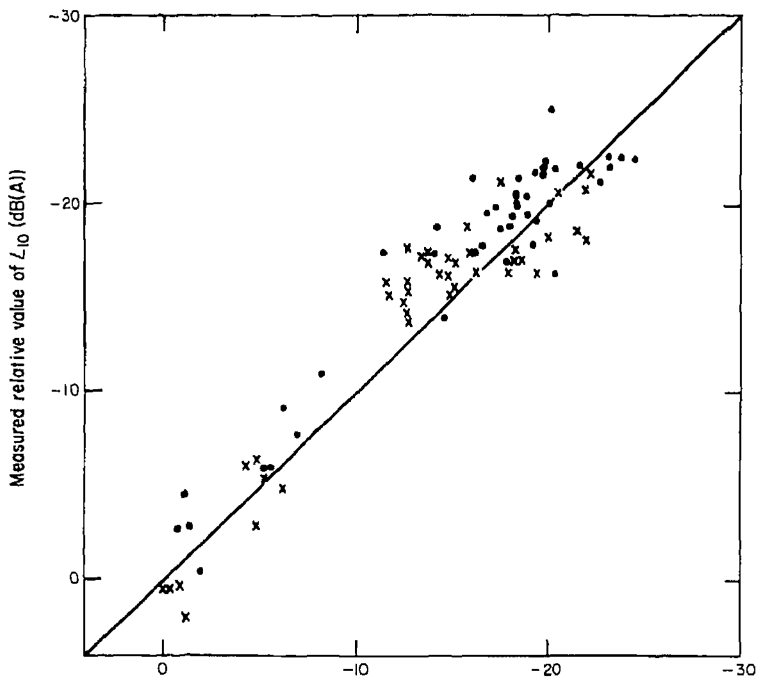

Figure 6. Prediction error for relative noise level for sites with houses predominantly parallel to the road. ●, Microphone 1·2 m high; ×, microphone 4 m high.

derive planning guidelines where such minor features cannot possibly be taken into account. Whether these detailed features lead to additional screening or, by reflecting sound into shadow zones, lead to reduced screening, their effects appear in this analysis as an error between field and model data and thus inflate the variance. In this connection it is significant that the mean error for the lower microphone, which is obviously more likely to be influenced by such obstacles, is nearly 1 dB(A) greater than that for the upper microphone. However, the mean attenuation associated with a particular type of site configuration can be specified much more closely than the corresponding values of rms error might at first sight indicate, and it is the mean attenuation which is important for planning purposes.

3.4. PROPAGATION ALONG SIDE ROADS

Comparisons of field and model results for noise propagating along three different side-roads leading approximately perpendicularly from a main road and along one curved (J-shaped) side-road are shown in Figure 7. The overall rms error is 2·12 dB(A) with $N = 61$.

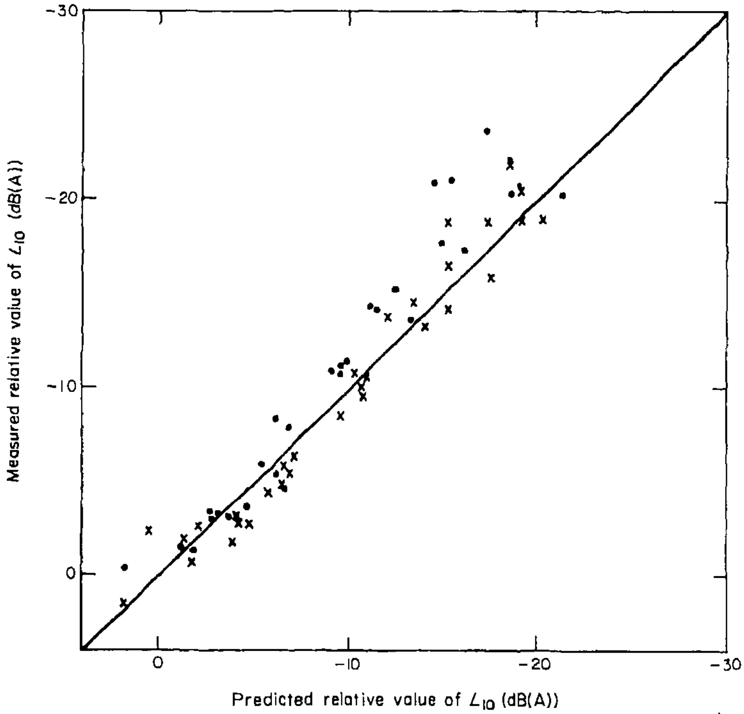

Figure 7. Prediction error for relative noise level for side-road sites. ●, Microphone 1·2 m high; ×, microphone 4 m high.

It appears that towards higher values the predicted attenuation for a microphone height of 1·2 m tends to be somewhat less than that measured in the field; in fact, the mean prediction error for a height of 1·2 m is 1·6 dB(A) whereas for a height of 4 m the prediction error is zero. As discussed above, it is probable that at 1·2 m the noise level in the field is significantly affected by obstructions in front of the houses (hedges, garden walls, even the occasional parked vehicle) which are not reproduced on the model, whereas at a height of 4 m such obstructions exert negligible influence on the prevailing noise level.

4. OVERALL PREDICTION ACCURACY

The above results indicate that, on the basis of the measurements confined to sites where the road is substantially level with the surrounding ground, prediction data obtained from the model technique correlate well with field data, the rms error varying from 1·7 dB(A) with simple well-defined sites to 2·4 dB(A) with complex urban sites. In the latter case a significant source of variance arises from the presence of purely local obstructions which are not reproduced on the model and are certainly not significant for planning purposes where the primary requirement is for typical data relating to a given class of site configuration. Moreover, although the precision with which the actual field measurements were made is such that negligible error was introduced, in all cases the field data themselves do contain a significant component of variance due to statistical sampling and due to the vagaries of the weather. When results obtained from modelling are used to predict relative noise levels for use by planners and road designers, the prediction error is probably significantly less than the rms figures quoted above but it is not possible to assert a definite upper limit for the error. In practical application the significance of any error depends very much on how much attenuation has been achieved. The critical area is often relatively close to the road and the difference between 5 dB(A) and 10 dB(A) attenuation might be quite significant, whereas at the already quieter locations a difference between 20 dB(A) and 25 dB(A) might be of more marginal significance. This is fortunate for the latter situation will be most affected by weather conditions, notably the wind strength and direction, and therefore liable to the largest prediction error. Indeed, whenever reduction of noise level is associated with refraction, diffraction or destructive interference of sound waves, changes in noise level due to weather conditions will be most noticeable where large attenuation has been achieved. By their very nature the values predicted by this modelling technique relate to low wind isothermal conditions and predicted values of noise reduction in excess of 25 dB(A) should be treated with some caution.

Using the model to predict for site configurations involving roads in cuts, etc., introduces an element of extrapolation for, to date, no systematic field data covering such situations have been available to us. However, there is no reason to believe that the validation studies described above are in any way specific so that a similar overall prediction accuracy should be maintained.

5. MODEL RESULTS FOR NEW SITE CONFIGURATIONS

Once it had been established that the modelling technique was capable of producing results substantially in accord with available field data the way was open to investigate new site configurations. The range of configurations for which prediction data are required is quite large and the primary objective of this study was not to investigate and produce prediction data for numerous situations but rather to establish the technique as a reliable prediction procedure so that others more directly concerned with traffic noise prediction could use it to obtain the required data. Nevertheless, the technique has been used to investigate propagation for a number of different site configurations and in the following a selection of these is outlined with the object of demonstrating its utility to cases which currently are not readily amenable to evaluation using other techniques.

5.1. PROPAGATION FROM A ROAD IN A CUT

One configuration offering considerable control over the spread of traffic noise from a major road is provided by running the road in a cutting. In order to minimize land uptake in urban areas a cut with near vertical retaining walls may be indicated and early model studies [3] showed that in such cases multiple reflection of sound between opposite sides of a retained cut has a significant (deleterious) effect on the screening achieved. However, even with highly reflecting retaining walls much of the degradation in shielding associated with multiple reflection can be avoided by inclining the side-walls outwards at an angle of 10° to 15° to the vertical. This work led to the relevant corrections included in the official procedure laid down by the Department of the Environment [27] which enables entitlement to sound insulation treatment for residential properties under the 1975 Noise Insulation Regulations to be determined.

Outside densely populated urban areas use will more often be made of natural cuts and in this situation multiple reflection does not occur. The scale model technique is also ideally suited to studying this type of site configuration and various widths and depths of cut have been investigated. By way of example Figure 8 shows relative values of L_{10} for a typical dual-carriageway in a 4·2 m deep natural cut. In order to derive these cross-sectional contours, data was obtained at over 120 observation points, corresponding to eight microphone heights and 16 different distances from the road (note that a small amount of fine detail in the immediate region of the top nearside corner of the cutting which were clearly resolved by the model has been omitted as irrelevant to the practical noise-prediction problem). The para-

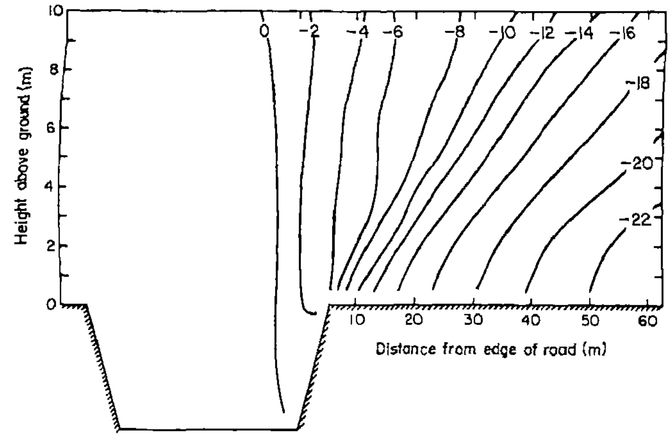

Figure 8. Noise contours showing relative values of L_{10} for a dual carriageway in a 4·2 m deep natural cut; reference is unobstructed noise level 10 m from the source line.

meter shows the value of L_{10} relative to the unobstructed level measured at a distance of 10 m from the source line. Whilst it may have been possible to derive such a set of contours from field data it would have been a time-consuming exercise and investigation of the systematic variation with depth of cut would certainly not have been possible. Thus the value of the model technique is evident.

5.2. PENETRATION OF NOISE THROUGH A GAP BETWEEN HOUSES

The field data obtained in connection with the validation exercise [26] showed that noise penetrating the gap between adjacent blocks of houses which were parallel to the road could in some circumstances lead to higher noise levels at the rear façade of the houses than might be expected on the basis of simplified prediction procedures. On an empirical basis the effect was ascribed to reflection of sound from obstructions such as garages or garden sheds erected immediately behind this gap. In the case of thin barriers (such as purpose-built noise barriers)

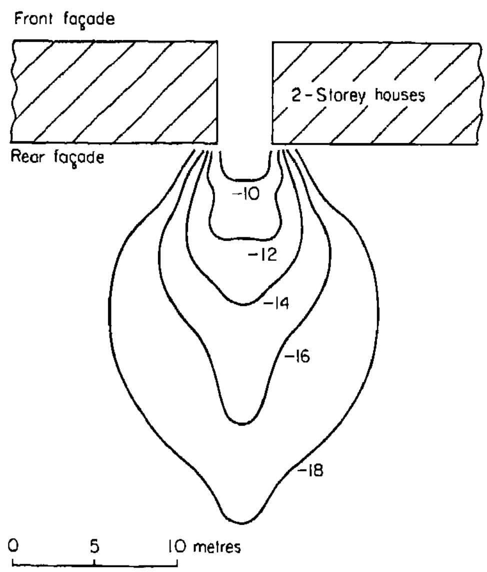

Figure 9. Penetration of traffic noise through a gap between blocks of two-storey houses; parameter gives value of L_{10} relative to unobstructed level at a distance of 10 m from the source line (microphone 1·2 m high, source line 24 m from front façade).

it has been shown that noise penetrating the gap can be accounted for simply on the basis of angle of view of the unobstructed traffic stream "visible" at any given measuring point [1] but such a procedure is appropriate to obstacles such as houses (which have substantial depth and between the end-walls of which sound can be multiply reflected) only when the measuring point is remote from the immediate region of the gap.

Model studies were therefore undertaken and Figure 9 shows data for a microphone height of 1·2 m for a typical gap (width 3·3 m) between blocks of two-storey houses; as before, the parameter is the attenuation relative to the unobstructed level at a distance of 10 m from the source line. Again, such contours would have been most difficult to obtain under field conditions but the requisite data were quickly and simply obtained by using the model technique. They can be used directly to predict the maximum effect due to erecting any substantial reflecting obstacle behind the gap.

A theoretical treatment of the penetration of noise through a gap between adjacent blocks of houses has been published recently by Yeow *et al.* [28].

5.3. CONTAINMENT OF TRAFFIC NOISE BY BUILDINGS

The augmentation of noise level due to containment by buildings is particularly amenable to study on the model scale since the arrangement of streets can be readily and systematically varied. For both continuous façades and façades with 50% open area, measurements of noise level have been made as a function of microphone height and of inter-façade distance,

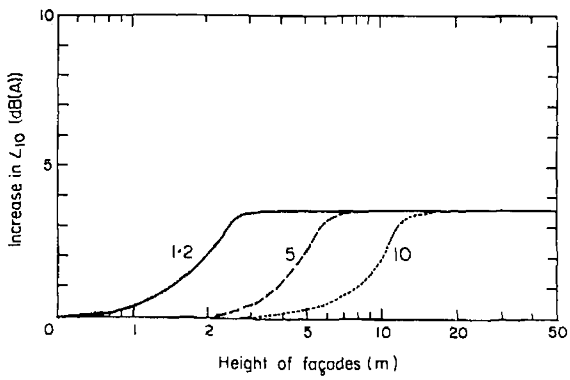

Figure 10. Increase in noise level L_{10} as a function of façade height for parallel unbroken façades 30 m apart; parameter is microphone height in metres.

and compared with levels prevailing when the site is completely unobstructed and when only a single façade is present. Although detailed samplings were taken, this is a case where contour representation of the noise field is not appropriate for only the façade noise level was of interest (viz. the noise level 1 m from the façade). Figure 10 shows mean results for the incremental change in L_{10} as compared with the free-field unobstructed noise level as a function of the height of the façades with microphone height as parameter. Each curve shows a plateau region when the façade height exceeds the microphone height by at least two metres and falls asymptotically to zero for façade heights less than the microphone height. Results for other interfaçade separations were broadly similar although the plateau level varied somewhat with road width and microphone height. The largest effect was found to obtain with high microphone positions in very narrow, tall canyons where increases of up to 6 dB(A) were found, but for interfaçade distances in the range 20 to 80 m the plateau level for all microphone heights was 3·5 ± 0·5 dB(A). As the increase due to the presence of a single façade was found to be approximately 2·5 dB(A), the additional increase due to containment is quite small. Indeed, as most façades will include at least some gaps, the containment effect under field conditions is likely to be even smaller than 1 dB(A).

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