Proceedings of the Institute of Acoustics

THE PREDICTION OF TRAFFIC NOISE LEVELS FROM COMPLEX HIGHWAY CROSS SECTIONS

D Tobutt, P M Nelson

Noise & Vibration Unit, Transport and Road Research Laboratory, Crowthorne, Berkshire, UK

1. INTRODUCTION

The method used by the Department of Transport for predicting the noise generated by road traffic is contained in the Technical Memorandum, "Calculation of road traffic noise" (CRTN) [1]. The method was developed by TRRL with the specific objective of providing a means of calculating entitlement for sound insulation treatment of residential properties as part of the powers given by the Noise Insulation Regulations of the Land Compensation Act of 1973. For these manual calculations the method had to be transparent and relatively simple. Although it copes well with fairly simple highway geometries, it is less able to deal with complex propagation problems involving both screening and reflection of the noise. Such situations can occur in urban areas where the presence of buildings located in close proximity to roads can introduce multiple reflections between facades and scattering, diffraction and screening. Similar phenomena can also occur for some motorway constructions such as deep vertical cuttings or where there are tall vertical noise screens located on either side of the road. Additionally the statutory method does not cater for the inclusion of purpose-built sound absorbing materials placed on the reflecting surfaces of barriers or cuttings, since it assumes that all such surfaces are highly reflective.

The model described in this paper has been formulated since the development of CRTN with the aim of providing a practical prediction method for complex traffic noise propagation conditions. A particular objective has been to determine a model which can be used to obtain a better understanding of the noise attenuation provided by roadway constructions which involve both screening and reflection of traffic noise such as retained cuttings, multiple barrier configurations and structures which involve a combination of these features.

2. FORMULATION OF THE MODEL

2.1 General

The modelling philosophy adopted has attempted to address all significant aspects of traffic noise generation and propagation. For example, the model includes consideration of the source strength, location, directivity, scattering by reflecting elements and attenuation with distance as a function of both the ground cover and the height of propagation. The principles of ray acoustics and image source modelling have been employed to account for both single and multiple reflections, absorption by surfaces and diffractions by the edges of barriers and screening walls. The formulation of the model is described fully in a report by Tobutt and Nelson [2]. The following sections give an overview of the various elements of the model, the validation studies that were carried out to determine the accuracy of prediction for different highway geometries and some examples of the use of the model to predict the screening performance of some idealised roadway constructions.

THE PREDICTION OF TRAFFIC NOISE LEVELS FROM COMPLEX HIGHWAY CROSS SECTIONS

2.2 Basic Assumptions

The model described in this paper is limited to single segment roadways, i.e. where the road effectively extends infinitely in a straight line either side of the reception point. For the types of highway construction and prediction problem envisaged, this represents a valid approximation to all but a few cases. The model can, however, be fairly simply extended to deal with situations which require the roadway to be divided into more than one segment [2]. The model requires the geometry of the highway to be defined along the cross-section drawn through the reception point along the normal to the source line. An example of a typical cross-section is given in Figure 1 for the situation where a dual carriageway is constructed in a cutting. It should be noted that the source lines are assumed to be located at the centre of each carriageway and 0.5 metres above the surface of the road.

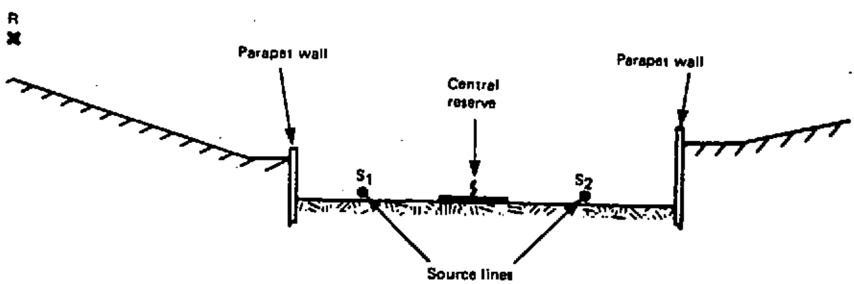


Fig. 1 Single segment roadway and cross-sectional geometry

2.3 Source strength and directivity.

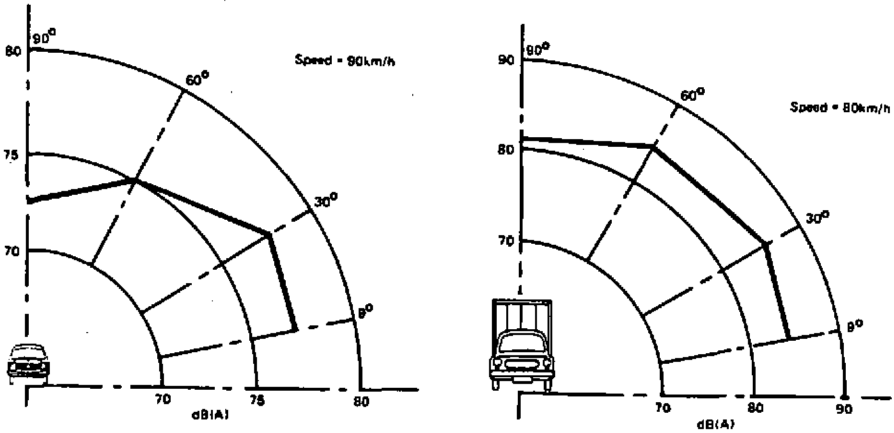
In this model the source strength is computed directly in terms of L_{A10} dB using the Department of Transport's method, 'Calculation of Road Traffic Noise' (CRTN). The functional form of the basic noise level described in CRTN was determined initially using both empirical and computer modelling techniques and has since been fully validated against an independent data set involving a data bank with over 2000 site measurements [3]. The form used, standardised for a horizontal road and a reference distance of 13.5 metres from the source line is given by:-

$$L_{A10} = -28.8 + 10 \, Log_{10} q + 33 \, Log_{10} (V + 40 + 500/V) + 10 \, Log_{10} (1 + 5p/V). \quad ..... (1)$$

Where q is the vehicle flow in vehicles per hour, V is the mean speed of the traffic stream in km/h, and p is the percentage of vehicles with an unladen weight greater than 1525 kg.

Modifications to the source strength according to the direction of propagation have been incorporated in the model. Previous models generally assume that the individual vehicles comprising the traffic stream radiate noise omnidirectionally so that the wave front expands in a hemispherical manner above the ground plane and the resulting line source generated by the traffic stream exhibits cylindrical spreading. In practice deviations from this simple rule can occur due, in part, to the individual directivities of different sources on the moving vehicles and to differential screening of these sources by parts of the vehicle when viewed from different angles. Consequently the noise propagating to receptor positions located above the traffic stream could be expected to differ appreciably from the noise radiated to receptors located nearer to the ground plane.

The directional characteristics of the source were calculated by averaging the polar plots obtained for noise radiated by individual vehicles under different operating conditions. These plots are reproduced in Figure 2. and were obtained from data reported by Ringheim and Storeheier [4] and Storeheier et al [5] for cars and lorries respectively. The figures show the much greater screening of the noise radiated by the vehicles in the vertical than the horizontal direction. This is particularly noticeable for the car group.



(a) Cars (from Ringheim & Storeheier, [4])

(b) Lorries (from Storeheier et al, [5])

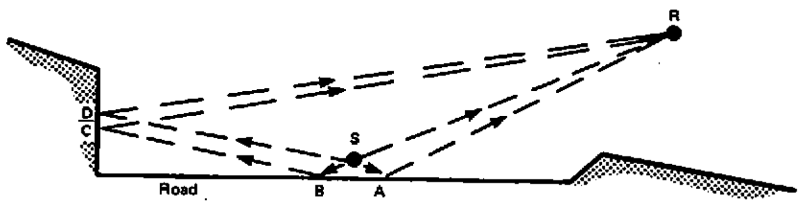
Fig. 2 Spatial distribution in a vertical plane normal to the travel direction of sound pressure levels for cars and lorries (distance 7.5metres)

2.4 Treatment of reflection and screening by barriers and walls

2.4.1 Reflection. The model includes in the formulation a consideration of the sound which is radiated from the source lines and is reflected by the various elements which form the cross-section. The absorbing characteristics of the surfaces involved are characterised by the Noise Reduction Coefficient $(NRC)_0$ which is the arithmetic average of the normal incidence absorption coefficients for 250, 500, 1000 and 2000 Hz. This is modified to take account of the angle of incidence of each relevant acoustic ray [2].

In the model the number of reflections of each acoustic ray is limited to two since it was found that in practice the influence of higher orders of reflection did not contribute significantly to the overall noise levels generated at reception points located alongside the road.

Figure 3 illustrates a typical cross-section showing the direct ray path constructed from the source line to the reception point and alternative viable ray paths involving primary and secondary reflections between the source and receptor.



Direct ray: S→R
Single reflection: S→A→R and S→D→R
Double reflection: S→B→C→R

Fig. 3 Illustration of ray paths drawn between the source, S, and the receiver, R, for a road in a cutting

2.4.2 Screening by Barriers. The method adopted in the model to deal with the screening afforded by acoustically thin barriers is based upon the well established semi-empirical relation determined initially by Maekawa [6] for the attenuation of point sources. The modification of Maekawa's point source function to account for barrier attenuation in relation to traffic noise (line) sources has been determined by several authors [7–10]. In the model the transform developed by Fisk [10] was used.

Further considerations are given to the screening provided by barriers which cannot be regarded as acoustically thin, eg, wedge shaped barriers, thick screens etc. For thick barriers an equivalent thin barrier is calculated in the model using the method described by Ford [11] and the Fisk transform of the Maekawa formula is then applied to the equivalent barrier. For wedge shaped barriers the diffraction attenuation is calculated using the method developed by Maekawa and Osaki [12]. This form of correction is important when dealing with the diffraction at the edges of retained cuttings.

2.5 Distance Attenuation

The propagation of traffic noise is affected by the ground surface between the source and the receptor. The determining factors are the separation of the source and the receiver, their heights above the ground and the acoustical absorbing characteristics of the surface. Despite the potentially complex effects introduced by the ground plane, for traffic sources it has been found experimentally [3,13] that, for a given height above ground, distance attenuation can be represented, to a good approximation, by a simple logarithmic function of distance. The form used in the model was derived from the attenuation function used in CRTN but was adapted to take account of propagation over a wider range of different ground surfaces. The function used in the model is:

THE PREDICTION OF TRAFFIC NOISE LEVELS FROM COMPLEX HIGHWAY CROSS SECTIONS

$$\text{Attenuation} = 10\log_{10}(d_s/d_o) + 12.1\,(NRC)_0 \log_{10}(d_s / d_o)\left[1 + \frac{\log_{10}[3/(6H-1.5)]}{\log_{10}[d_s/3]}\right] \quad .....(2)$$

where d_s is the distance from the source to the receptor, and d_0 is a reference distance from the source line normally taken to be 13.5 metres for traffic noise prediction purposes. H is the mean height of the propagation path above the ground drawn between the source and the receptor, and it is required that $0.75 < H < (d_s + 1.5)/6$. $(NRC)_0$ is the normal incidence Noise Reduction Coefficient used to characterise the acoustical properties of the ground under the propagation path. Values of $(NRC)_0$ for different types of ground cover are given by Tobutt and Nelson [2].

It should be noted that for a hard, reflecting surface such as concrete, $(NRC)_0 = 0$ and the attenuation is then given by the first term in equation (2) which is the familiar form of the attenuation function for propagation over a reflecting surface. Similarly, when the height of the propagation is well above the ground plane such that $H \geq (d_s + 1.5)/6$ the absorbing characteristics of the ground are assumed to have no effect on the propagation. For these conditions, attenuation function again reverts to the reflecting ground condition i.e. the first term only of equation (2).

3. VALIDATION OF THE MODEL

3.1 General

The model has been tested by comparing predicted values of L_{A10} with noise measurements taken at different sites. Additionally the method has been compared with data obtained from scale models. In order to carry out the necessary calculations a computer program known as CROSECT was developed which was designed to run on a small desk-top computer. The program requires as input the dimensions of the cross-section in terms of the end point coordinates of a series of connecting straight line elements. These data are entered together with the values of $(NRC)_0$ assigned to each element of the cross-section. The source and receptor positions are also defined at the input stage together with basic traffic flow parameters, the road gradient and the texture depth of the road surface. The program computes values of L_{A10} either at previously defined receptor positions or in the form of a two dimensional map of the noise levels drawn in the same plane and scale as the cross-section. Contours of the L_{A10} values can be achieved using a specialised contouring package.

3.2 Comparison with Site Data

A total of 18 road sites were located covering a broad range of highway cross-sections where access for noise measurement was possible. These included sites with noise barriers, cuttings with both vertical and sloping walls, and more complex sites which combined several of these features. The main objective in the selection of sites was to provide a rigorous test of the absolute prediction accuracy of the model as formulated in the CROSECT program. Figure 4 gives the cross-section studied at 4 of the chosen sites. The approximate positions of the measurement points are indicated on the Figure.

THE PREDICTION OF TRAFFIC NOISE LEVELS FROM COMPLEX HIGHWAY CROSS SECTIONS

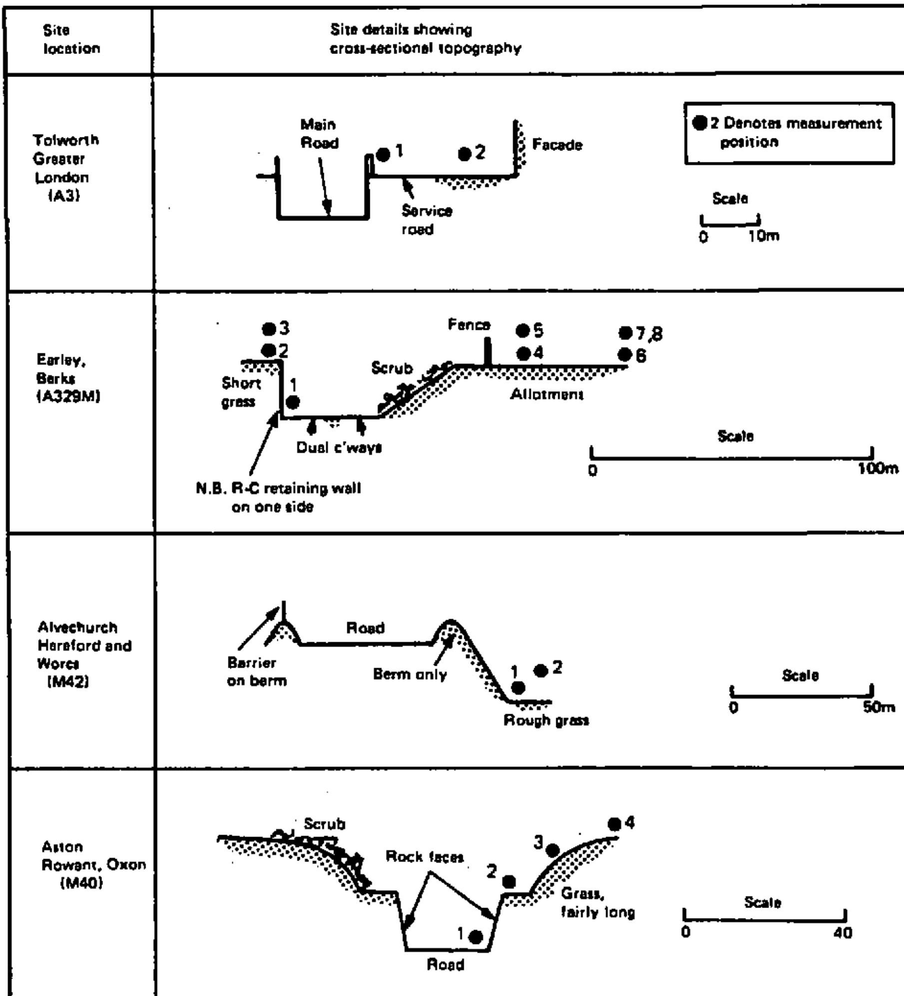


Fig. 4 Examples of sites used to test the accuracy of the prediction models

The noise measurements were taken using ½" omnidirectional condenser microphones connected to a portable noise analyser which computed the L_{A10} noise level over a period of 20 to 30 minutes. Measurements were only taken during periods of dry weather and when the wind was slight. During the recordings measurements were taken of the traffic flow and the numbers of vehicles in the heavy vehicle class (> 1525 kg unladen weight). The mean speed of the traffic was estimated from the speed limit and road classification using the method described in CRTN (1988) [1] and the road gradient was determined from the site map. Details of the cross section were obtained from large scale (1:1250) maps of the sites and from measurements taken on site with a theodolite.

Figure 5 gives the results of the comparison between the predicted values of L_{A10} using CROSECT and the site measurements. A statistical analysis of the distribution of errors (predicted – measured) showed that the mean error was –0.24 dBA with a standard deviation of 1.82 dBA. This standard of prediction accuracy is generally regarded as being very satisfactory. A comparison using the CRTN model with the same data gave a mean error of +1.39 dBA with a standard deviation of 2.96 dBA.

Although the comparison indicates that the errors produced by CRTN are substantially greater than that produced by the CROSECT model, it must be noted that CRTN does not cater for reflection from absorbent surfaces and the attenuation with distance function used in the CRTN does not cover highly absorbing ground conditions.

3.3 Comparison with scale models
In addition to comparing the predictions with site data, a comparison was also made between predictions obtained using CROSECT and measurements taken using a 1:30 scale model developed by Delany et al [14]. In this scale model a range of road geometries, principally cuttings, were modelled in an anechoic chamber. The sound source was an air jet mounted in close proximity to a sharp edge. The effect was to produce a broad band high frequency sound source which, with suitable enclosure design, was made to radiate in a roughly omnidirectional manner. The source was mounted on a sledge which was drawn through the model at a constant speed to simulate the drive-by of a single vehicle. In the scale model the ground cover was chosen to represent an absorbing grassland surface by scaling the porosity and air resistivity to values found to be typical for grassland. The attenuation with distance function used by the CROSECT program was matched with the scale model characteristic by iterative adjustment of the ground cover absorption coefficient, initially taking values which were representative of short grass. Figure 6 shows a general comparison between the results obtained using the scale model and the predictions made using the CROSECT program. In the Figure the attenuations compared are in terms of the L_{A10} and refer to the differences between the values at the reception point and the value determined at a reference distance of 7.5 m from the source line. The data compared in the Figure represents a broad range of retained cuttings with depths of cut ranging between 2 to 6 m and receptor positions located between 2 and 4 m above ground and between 10 and 100 m from the edge of the cutting. The data in the Figure differentiates between retained cuts which have reflecting surfaces , ie with $(NRC)_o$ = 0.02, and cuttings fitted with absorbent linings, ie with $(NRC)_o$ = 0.90.

A statistical analysis of the differences (CROSECT minus scale model) showed that for the data set of 113 points the mean error was –0.4 dBA with a standard deviation of 1.66 dBA, which, as before, demonstrates a very close degree of overall prediction accuracy.

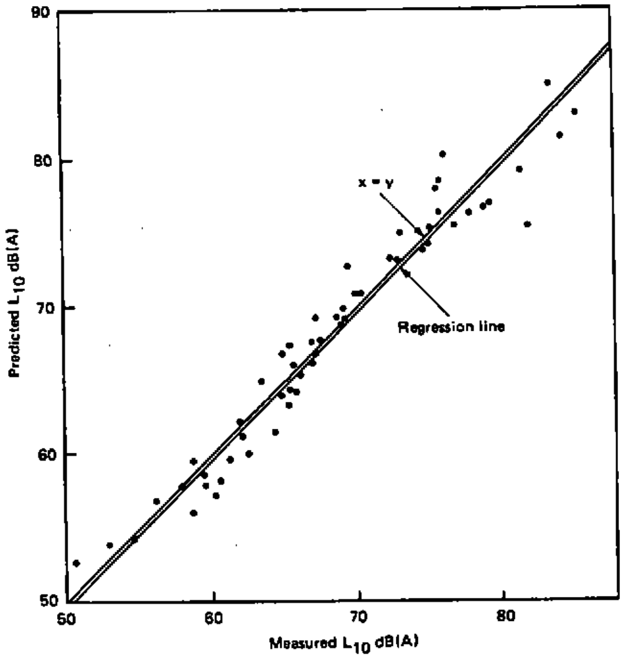


Fig. 5 Comparison of measured and predicted levels of L_{10} dB(A) using the CROSECT model

4. APPLICATIONS OF THE MODEL

Having established the validity of the method it is possible to use the model with some confidence to examine the relative screening performance of different highway cross-sections including the use of absorbing panels fitted to barriers and cuttings. The following gives two examples of the use of the model to predict screening performance of barriers and cuttings. Clearly, since there are potentially a very large number of design possibilities that could be examined, the following sections will only highlight some of the general features to emerge from the use of the program. Further examples are given in the paper by Tobutt and Nelson [2].

4.1 Screening by absorbing barriers

To examine the effects of fitting absorbing faces to barriers, calculations have been carried out using CROSECT for an idealised motorway cross-section where there is a plane vertical barrier located symmetrically on either side of the road. Using this configuration, contours of L_{A10} were produced in the

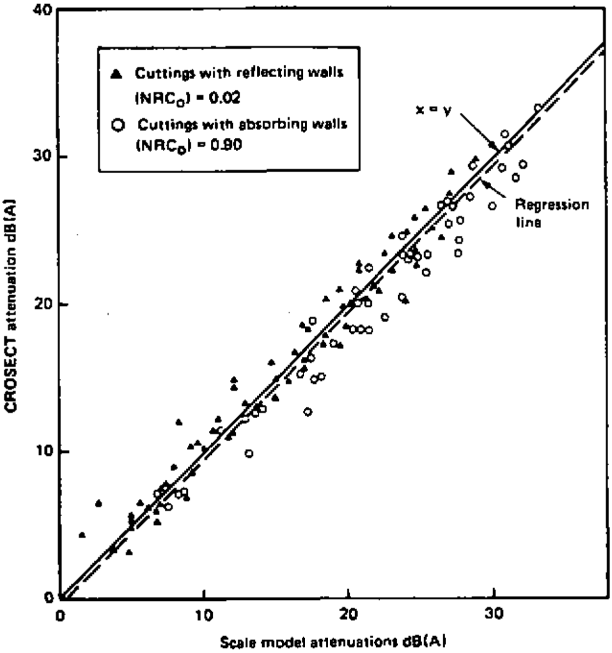


Fig. 6 General comparison of noise level attenuations obtained for various retained cut configurations using 'CROSECT' and a 1:30 scale model developed by Delany et al

2–dimensional space behind the screening barrier for the condition where the barriers were of the reflective type, with low absorption coefficients, $(NRC)_o$ = 0.02, and for the case where the barriers were highly absorbing with $(NRC)_o$ = 0.83. This latter figure was found to be appropriate for an actual barrier panel. The differences in the contour plots between the 2 conditions were then determined. The results of this calculation are shown for 2 barrier heights in Figure 7. In this example the roadway was modelled to represent a dual 3–lane carriageway with a road width of 50 m, including the hard shoulders. The traffic stream sources were located at the centre of each carriageway and 0.5 m above the road surface.

The Figure shows that the absorbent face produces significant reductions in the L_{A10} sound field located behind the screening barrier for both barrier heights considered. The reductions achieved, in excess of those achieved by the reflecting barriers, are generally between 2 and 3 dBA for most of the region where, in practice, conventional dwellings might be located. As expected, a greater improvement is achieved for the taller barrier, although for this particular configuration, where both barriers are the same height, the noise reductions due to the absorber exhibit only a marginal improvement with barrier height. It is worth noting, however, that the L_{A10} contours do exhibit a significant shift in the vertical direction with increasing barrier height which could be a useful design consideration when attempting to screen sensitive areas in the receptor field.

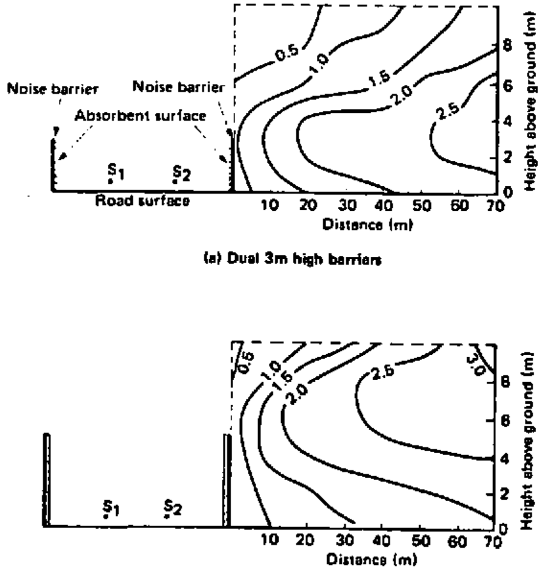


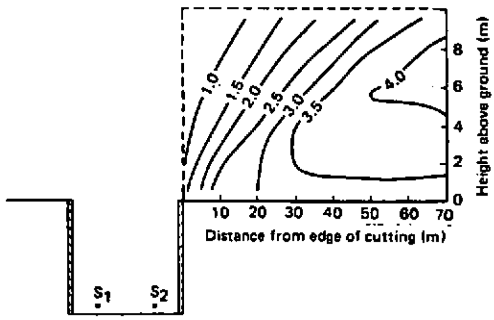
Fig. 7 Differences in L_{10} dB(A) for dual barriers with and without absorbent. (Posted values are L_{10} (without absorbent) – L_{10} (with absorbent); $(NRC)_0$ for absorbent = 0.83)

4.2 Design of cuttings for noise control

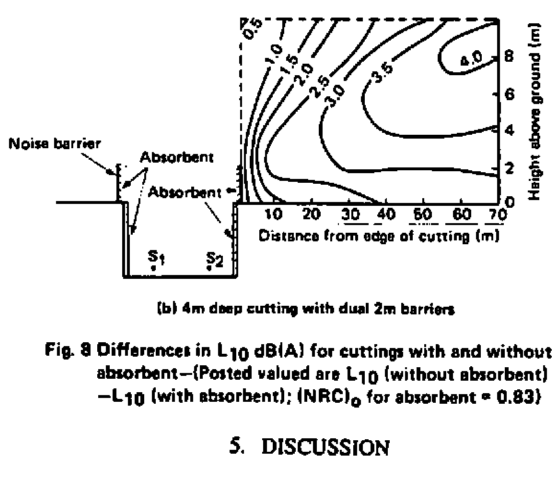
The CROSECT program can be used to determine both the screening provided by cuttings of different cross-section design and also to investigate the performance of absorbing materials fitted to the facing walls. Figure 8a shows the results of a calculation carried out using CROSECT for a vertical cutting 6 m deep lined with absorbent materials. As before values of the contours plotted in the receptor field are differences between the noise levels produced with reflective walls and with absorbing retaining walls. It can be seen that the results are similar to, although slightly greater than, those obtained for the dual barrier cases.

Cuttings are often constructed with some form of barrier located close to the edge for reasons of both safety and noise control. Figure 8b shows the results of a calculation using CROSECT for a 4 m deep cutting combined with dual 2 m high acoustic barriers. Again, the contours relate to the reduction in L_{A10} when adding absorbent facings to the barriers and cutting, as shown. In this case the improvements obtained using the absorbent treatment are similar to those achieved for the 6 m deep cuttings.

THE PREDICTION OF TRAFFIC NOISE LEVELS FROM COMPLEX HIGHWAY CROSS SECTIONS



(a) 6m deep cutting



(b) 4m deep cutting with dual 2m barriers

Fig. 8 Differences in L_{10} dB(A) for cuttings with and without absorbent—(Posted valued are L_{10} (without absorbent) $-L_{10}$ (with absorbent); $(NRC)_0$ for absorbent = 0.83)

5. DISCUSSION

The mathematical model described in this paper has been constructed with the aim of providing a practical prediction method for complex traffic noise propagation conditions. A particular objective has been to determine a model which can be used to obtain a better understanding of the noise attenuation provided by roadway constructions which involve both screening and reflection of traffic noise such as retained cuttings, multiple barrier configurations and structures which involve a compilation of these features.

The modelling philosophy adopted has attempted to address all significant aspects of traffic noise generation and propagation. For example, the model includes consideration of the source strength, location and directivity; the scattering by reflecting elements; and attenuation distance as a function of both ground cover and the height of propagation. The principles of ray acoustics and image source modelling have been employed to account for both single and multiple reflections, absorption by surfaces and diffractions by the edges of barriers and screening walls.

By adopting this comprehensive and pragmatic approach to the formulation of the model it has been possible to predict, with reasonable confidence, both the insertion loss characteristics provided by different idealised roadway cross-sections and the absolute values of L_{A10} for real road situations where propagation conditions are wide ranging and complex. The model therefore provides the user with both a practical design tool which can be used to investigate basic design concepts and a prediction method of general application which can be used to calculate performance of actual road schemes over the full range of receptor locations.

The model can be used to identify and rank order the principle rays affecting propagation of a given roadway cross-section. Using this facility, it is possible to associate positioning of absorbent material or the determination of shape or angle of a reflecting wall with the control of the dominant acoustic rays which affect the levels of noise at sensitive receptor locations. This particular facility of the program could also be linked to other features of design such as costs and maintenance. For example, in general it is unlikely that the lower parts of barriers will be found to contribute to the reflected component at most receptor locations, and so it may not be necessary to place costly absorbing material in this region.

The extension of the model to cater for multiple segments would provide a useful link towards the development of a more comprehensive program for complex screening conditions. For example, in association with the work reported here a program has been developed at the TRRL which optimises the dimensions of a barrier or screening wall in terms of its length and height and distance from the source line for a given source and receptor location and noise level insertion loss. It would be possible, therefore, to combine a multiple segment version of CROSECT with the optimisation program to provide a method which will give design guidance on both cross-sectional geometry and the longitudinal profile, and which will also seek to reduce the cost of the construction by determining the optimum dimensions and location of the screening wall for a specified level of noise reduction.

6. CONCLUSIONS

1. A semi-empirical model has been constructed for the prediction of traffic noise L_{A10} dB for conditions where the propagation of traffic noise is complex.

2. The model formulation has been incorporated in a computer program known as CROSECT. This program utilises ray tracing and image source theory to account for reflection, absorption and diffraction associated with barriers and cuttings.

3. Overall the prediction accuracy of the CROSECT model was considered to be highly satisfactory for a broad range of complex propagation conditions.

4. Further development of the model could include enhancing its ability to deal with multiple line source segments and longitudinal screening and to couple this with cost minimisation.

7. ACKNOWLEDGEMENTS

The work described in this paper forms part of the programme of the Transport and Road Research Laboratory and the paper is published by permission of the Director.

8. REFERENCES

[1] DEPARTMENT OF TRANSPORT AND WELSH OFFICE, "Calculation of Road Traffic Noise". London, H M Stationery Office (1988).

[2] D C TOBUTT & P M NELSON, "A Model to Calculate Traffic Noise Levels from Complex Highway Cross-Sections". Transport and Road Research Laboratory, Research Report 245 (1990).

[3] M E DELANY, D G HARLAND, R A HOOD & W E SCHOLES, "The Prediction of Noise Levels L10 due to Road Traffic". Journal of Sound & Vibration 48(3), 305-325 (1976).

[4] M RINGHEIM & S A STOREHEIER, "Noise from Motor Vehicles. Part 1 - Private Cars". Electronics Research Laboratory (Acoustics). Norwegian Institute of Technology (1972).

[5] S A STOREHEIER, K SKAALVIK & M RINGHEIM, "Noise from Motor Vehicles. Part 2 - Heavy Vehicles". Laboratory of Acoustics, Dept of Electrical Engineering, Norwegian Institute of Technology (1973).

[6] Z I MAEKAWA, "Noise Reduction by Screens". Applied Acoustics 1, p 157 (1969).

[7] M E DELANY, "A Practical Prediction Scheme for Predicting Noise Levels L10 arising from Road Traffic. NPL Report AC 57 (1972).

[8] W E SCHOLES, A C SALVIDGE & J W SARGENT, "Barriers and Traffic Noise Peaks". Applied Acoustics 5, p 205 (1972).

[9] DEPARTMENT OF THE ENVIRONMENT, "New Housing and Road Traffic", Design Bulletin 26. London, H M Stationery Office (1972).

[10] D J FISK, "Attenuation of L10 by Long Barriers". Journal of Sound & Vibration 38(3), p.305 (1975).

[11] R D FORD, "The Physical Assessment of Transportation Noise". Chapter in "The Transportation Noise Reference Book; P M Nelson, editor. Butterworths, London p.10/6 (1987).

[12] Z I MAEKAWA & S OSAKI, "A Simple Chart for the Estimation of the Attenuation by a Wedge Diffraction". Applied Acoustics 18, p. 355 (1985).

[13] M E DELANY, "Prediction of Traffic Noise Levels". NPL Report No. Ac56 (1972).

[14] M E DELANY, A J RENNIE & K M COLLINS, "Scale Model Investigations of Traffic Noise Propagation". N P L Acoustics Report AC58 (1972).