COST-BENEFIT ANALYSIS OF THE APPLICATION OF TRAFFIC NOISE INSULATION MEASURES TO EXISTING HOUSES

D. Modra
vironment Protection Authority, Melbourne

W. Bennett
partment of Civil Engineering,
iversity of Melbourne

STRACT:

Many houses facing onto arterial roads in major cities are significantly impacted by road traffic noise which cannot be reduced in the short to medium term through vehicle noise controls. Where an immediate reduction in the noise impact is required the only realistic option is to retrofit noise insulation measures to the houses affected.

Six stages of noise insulation are identified. Five are for the house itself, the remaining stage being a barrier fence at the property line. Typical installation costs and noise reductions for each stage also are identified.

The property value approach is used to place a dollar value on the benefit arising from the noise reduction of each of the stages of insulation. Five of the six stages are found to be justifiable on the basis of cost-benefit analysis. The sensitivity of the results to changes in benefit and cost components is examined and the effects of budgetary constraints analysed.

INTRODUCTION

Road traffic constitutes by far the major source of noise in large cities (OECD 1980, p ii) and many countries have introduced programs to tackle this problem. The erection of traffic noise barriers along freeways and major highways is now relatively common. Some countries have compensation schemes that cover the cost of noise insulation measures for houses exposed to excessive levels of traffic noise from new or altered roads, and programs to "retrofit" such measures to houses adjacent to existing major roads are becoming more common (Modra and McIntosh 1983). One of the conclusions of a recent OECD conference on noise abatement policies was that external daytime noise levels in the proximity of housing should not exceed 65 dB(A) L_{eq}[1] (OECD 1980, p vi), and many of the programs summarized by Modra and McIntosh use this criterion (although some countries use 65 dB(A) L_{eq} (24 hour) as the upper limit of acceptability[2].

In 1976 the Victorian Environment Protection Authority (EPA) developed a guideline that effectively limits the noise due to new freeways to 68 dB(A) L_{10} (18 hour)[3] at one metre from the facade of any house (EPA 1983a, p 7). Because traffic noise research has shown that the L_{10} value for traffic noise over any given time interval exceeds the L_{eq} value over the same interval by very close to 3 dB(A), there is reasonably good agreement between the OECD and the Victorian EPA criteria (Saunders and Jameson 1978, p 13). It has been the responsibility of the Country Roads Board (now the Road Construction Authority) to design its facilities to the EPA criterion, and the 8.5 km of earth and timber noise barriers constructed by the CRB along freeways since 1976 are tangible evidence of the EPA guideline (Stone and Saunders 1982, p 117).

Houses facing arterial roads in Melbourne are not covered by the EPA guideline, yet most are significantly impacted by road traffic noise. This problem cannot be solved in the short to medium term through vehicle noise controls. Where an immediate reduction in the noise impact along arterial roads is required the only realistic option is to retrofit noise insulation measures to the properties affected. This paper uses cost-benefit analysis to determine the optimum level of traffic noise insulation for a house believed to be typical of many facing arterial roads in Melbourne. As the optimum noise insulation package for this house is found to cost $4825 (1983 dollars) the massive funding needed to support a retrofit program can be appreciated.

THE EXTENT OF NOISE IMPACT DUE TO ARTERIAL ROADS

Modra (1979) has estimated that 85% of the houses adjacent to major thoroughfares in Melbourne are exposed to traffic noise levels over 68 db(A)

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[1] L_{eq} is the energy equivalent noise level.

[2] L_{eq} (24 hour) is the energy equivalent noise level evaluated over a 24 hour period.

[3] L_{10} is the level of noise exceeded for 10 percent of a specified interval of time, eg. L_{10} (1 hour). L_{10} (18 hour), however, is the arithmetic average of the eighteen L_{10} (1 hour) levels for the time interval between 6 am and 12 midnight.

L_{10} (18 hour). (The data base included some sites adjacent to freeways). The results of this study are summarized in Figure 1. A more recent, unpublished, estimate made by EPA in 1983 puts this figure at 81%. These results are indirectly supported by the following statement in the Pascoe Vale Road Relief Study Environmental Effects Statement (Ministry of Transport 1984, p 43). "It can be seen that a house adjacent to a road carrying only 8000 vehicles per day (with no trucks), or 4500 vehicles per day with 10% trucks, a low volume arterial road, would experience noise levels of 68 dB(A)".

Modra (1984) has analysed the noise levels in streets parallel and perpendicular to arterial roads to establish whether the facade levels are likely to exceed 68 dB(A) L_{10} (18 hour). This analysis used EPA data and results reported by Beranek (1971). Modra concludes that houses facing minor streets parallel or perpendicular to arterial roads are not likely to be exposed to facade levels greater than 68 dB(A) L_{10} (18 hour). The significance of this result is that, if unacceptable impact is taken as occurring at levels of 68 dB(A) L_{10} (18 hour) and above, then the impact of traffic noise from arterial roads can be considered to be limited to the houses facing directly onto these roads. If a traffic noise insulation retrofitting scheme were to be introduced with a 68 dB(A) L_{10} (18 hour) eligibility criterion, then most but not all houses facing arterial roads would be eligible.

QUANTIFICATION OF BENEFITS : THEORY

The Group of Economic Experts of the OECD Environment Committee has indicated (OECD 1982, p 5) that "significant progress has been made over the past ten years in developing the methodologies for estimating environmental damage cost (the inverse of benefits), in certain cases reaching a high degree of sophistication". For example, where houses are impacted by traffic noise the OECD Economic Experts recommend the use of a noise depreciation index of 0.5% of property value per decibel change in traffic noise level when estimating damages or benefits. Modra (1984) reviews and summarizes the literature in this field.

Freeman (1979, p 3) defines benefits as "the values that individuals place on reducing the adverse effects of pollution". The benefit of an environmental improvement is therefore the sum of the monetary values assigned to the improvement by those directly or indirectly affected. Determining these values is difficult because environmental quality is not traded in an explicit market.

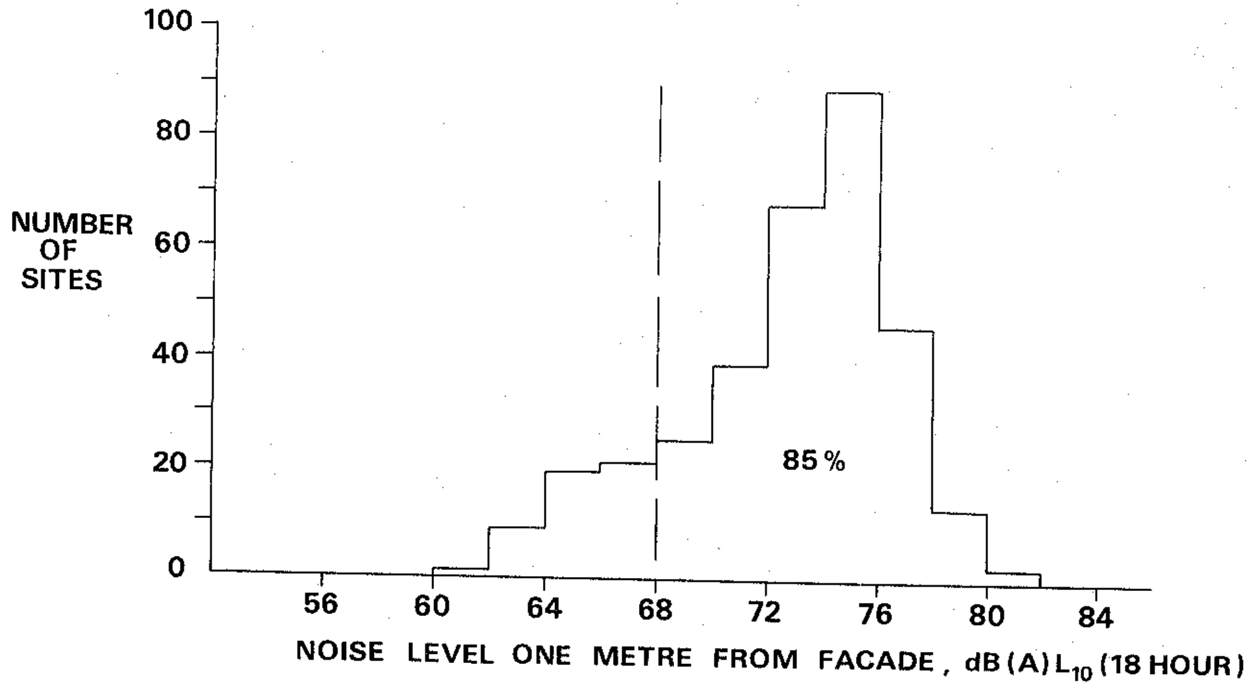
Freeman identifies three basic approaches to determining the values that individuals place on improvements in environmental quality. These are:

1. Ask individuals to reveal directly their willingness to pay for stated levels of environmental quality, or the quality they would demand at a stated price. This could involve interviews or surveys and is a non-market approach.

2. Place proposals for alternative levels of environmental quality to referendum vote. Under certain circumstances the outcome of the voting process will reveal information about the underlying demand for environmental improvement. This is another non-market approach.

3. Analyse data from market transactions in goods and services related to environmental quality. For obvious reasons this is referred to by Freeman as a market approach.

FIGURE 1 PREDICTED NOISE LEVELS FOR 332 SITES ON BUSY THOROUGHFARES IN MELBOURNE



There is no evidence that the first two (non-market) approaches have been used to derive a result that is of relevance here. The market approach, however, leads to several empirical techniques for estimating the demand for environmental improvements. One of these (the Hedonic Price Technique) provides the theoretical basis for all the studies which have yielded useful depreciation indices for traffic noise. These studies are called house price or property value studies.

The Hedonic Price Technique Applied to House Prices

When using the hedonic price technique, houses are viewed as belonging to a product class differentiated by characteristics such as the number of rooms, the block size and the exterior traffic noise level. Multivariate statistical methods, commonly multiple regression analysis, are used to determine from data for a number of housing transactions the (regression) coefficients for each characteristic. These coefficients are interpreted as implicit or hedonic prices where the hedonic price gives the change in house price (or property value) due to a one-unit change in the amount of the characteristic. For example, where traffic noise is a characteristic, the relevant hedonic price is the change in house price per decibel change in traffic noise level. A noise depreciation index (N.D.I.) is an hedonic price expressed as a percentage of property value.

Nelson (1978, p 69) indicates that the basic empirical relationship underlying the hedonic price technique has the general form:

$$P = zB + e$$

where P is an $n \times 1$ vector of observations on prices for n products (in this case, houses), z is an $n \times k$ matrix of observations on the k characteristics ($k < n$) of these products, B is a $k \times 1$ vector of coefficients associated with the characteristics, and e is an $n \times 1$ vector of stochastic disturbances.

Basic Requirements for an Analysis of the Effects of Environmental Noise on House Prices

Taylor et al (1982) identify four basic requirements for an analysis of the effects of traffic noise on house prices using the hedonic price technique. These are:

1. Disaggregate data on individual housing transactions. (Some North American studies have used average house prices within census tracts).

2. Full information on the internal, locational and neighbourhood characteristics for each transaction.

3. Temporal and spatial standardizing of house prices.

4. Measurements or accurate predictions of the traffic noise level for each house included in the analysis. (Some North American studies have used a single noise exposure value to represent a census tract).

These requirements are met to a greater or lesser extent in the eight house price studies discussed in the next Section.

QUANTIFICATION OF BENEFITS : PROPERTY VALUE STUDIES

Five North American and three Australian Property Value Studies are summarized in some detail by Modra (1984). Very abbreviated summaries of these studies are presented below.

North American Studies

The study-report authors and the publication dates are: Gamble et al (1974), Nelson (1975), Vaughan and Huckins (1975), Anderson and Wise (1977), and Taylor et al (1982). The noise depreciation indices derived from each of these studies are given in Table 1, together with other relevant information.

Gamble et al were the first to conduct a major study of the effects of traffic noise on residential property values. The Anderson and Wise study used the same data set as Gamble et al and was designed as a follow up to their study. Anderson and Wise screened the sales-price data for recording errors and deflated these prices by the consumer price index in the appropriate geographic area.

Nelson determined hedonic prices for each of the following thirteen housing and neighbourhood characteristics: median number of rooms per unit, median lot size in square feet, percentage of units greater than 30 years old, percentage of units having central air conditioning, "percentage of units lacking a flush toilet" (Nelson 1978, p 229), proximity to Potomac and Anacostia rivers, neighbourhood racial composition, average monthly particulate concentration of the ambient air, average summer oxidant concentration in the ambient air, time in minutes to reach 75 percent of metropolitan employment, percentage of tract area in industrial categories of use, and the average day-night sound level.

Vaughan and Huckins did not include a measure of ambient air quality in their set of housing and neighbourhood characteristics. It is therefore possible that the hedonic price for traffic noise captures other disamenity effects of traffic, and overstates the effect of traffic noise on house prices.

In the Taylor et al study, each sampling unit was a residential site which comprised up to three rows of housing parallel to a major road. Only sites with very similar housing from row to row were included. Taylor et al include analyses of within-site and between-site effects.

Australian Studies

Jarvie (1978) has reported on a study which assessed the impact of traffic noise on the prices of houses in Newcastle. Unfortunately it is not possible to calculate NDI values from Jarvie's data because the data set does not include noise levels and other housing characteristics which contribute to differences in property values.

Abelson (1977) analysed the prices of all houses sold in the Sydney suburbs of Marrickville and Rockdale between January and September 1973. It is possible to estimate an NDI value from Abelson's results. If the difference in noise level between "noisy" and "quiet" is taken as 10 dB(A) (which is plausible although probably an underestimate) then the results for Marrickville would imply an NDI value of 0.56%.

Holsman and Bradley (1982) have recently carried out a major study of the relationship between traffic noise and house prices in Sydney. Their

TABLE 1. NORTH AMERICAN PROPERTY VALUE STUDIES

Author(s) (Year of Publication)	Location	Year(s) of Property Transactions	Range of Traffic Noise Levels, dB (Noise Scale)*	NDI, %
Gamble et al (1974)	Bogota (New Jersey), Towson (Maryland), Roseland (Maryland), North Springfield (Virginia)	1969 to 1971	30 (NPL)	0.26, pooled data
Nelson (1975)	Washington DC	1970	31 (L_{dn})	0.8
Vaughan and Huckins (1975)	Chicago	1971 and 1972	24 (L_{eq})	0.6
Anderson and Wise	as for Gamble et al	1965 to 1971 (i.e. increased sample size)	30 (NPL)	0.25, pooled data
Taylor et al	Toronto, Hamilton (Southern Ontario)	1972 to 1978	35 (L_{eq})	0.5

* Noise Scales (see Schultz (1982))

NOTE: In all cases the units are decibels.
NPL = Noise Pollution Level.
L_{dn} = average day-night sound level.
L_{eq} = energy average sound level.

study involved a comparison of property prices on main roads with those on adjacent parallel roads, and is in some respects similar to the study of Taylor et al (1982). The data set comprised 1306 house sales over the period 1968 to 1980. Holsman and Bradley do not aim to develop noise depreciation indices, and none are quoted in their text. Modra (1984) has developed approximate NDI values from Holsman and Bradley results. These are based on the average yearly difference in mean house prices for main roads and parallel streets and are listed in Table 2.

The Effect of Multicollinearity

Each of the property value studies summarized above can be critized for omitting important traffic related neighbourhood characteristics such as pedestrian safety and traffic congestion. As a result, the traffic noise variable "picks up" these highway disamenities. Consequently, the traffic noise NDI is "probably biased upwards due to the intercorrelations with other neighbourhood disamenities", (Nelson 1978, p 122). Nelson also indicates (1978, p 95) that NDI values "should be interpreted as a maximum estimate of the effects of traffic noise on property values".

Because of this bias the cost-benefit analysis presented in this paper is carried out in two stages. Firstly, the optimum amount of noise insulation is determined using a typical NDI value selected in this Section. Then the sensitivity of the result to reductions in the NDI value is analysed in some detail.

Selection of Typical NDI Value

The NDI values reported in or derived from the North American and Australian property value studies are set out in Table 2. On the basis of this data it seems reasonable to accept the previously mentioned OECD recommendation and use an NDI value of 0.5% of house price per dB(A) change in traffic noise level.

STAGES OF NOISE INSULATION

Six stages of noise insulation are shown in Table 3. These have been adapted from work done by the CSIRO Division of Building Research (CSIRO 1977 and 1978) and the (US) Wyle Research Laboratories (Davy and Skale 1977, and Sutherland 1978). This work is summarized in some detail by Modra (1984). For each stage of noise insulation an increment of noise reduction is identified. Using the noise depreciation index selected in the previous section it is possible to calculate incremental benefits directly from the incremental noise reductions. Cost data are assembled in the next Section, and the cost-benefit analysis follows this.

It must be emphasized that for only one of the six stages of insulation (the barrier) can the noise reduction be determined with any precision. In all other cases the noise reduction achieved will depend on two factors: the acoustic properties of the insulation measure itself, and the acoustic properties of the building to which it is applied. Under these circumstances it is only possible to quote a range of reductions for each measure from which a mean value can be calculated.

Comments on each of the insulation stages are set out below.

TABLE 2. SUMMARY OF NDI VALUES

STUDY; LOCATION	BEST NDI ESTIMATE (% OF HOUSE PRICE PER dB(A))
NORTH AMERICA	
Nelson; Washington.	0.8
Gamble et al; New Jersey, Maryland and Virginia.	0.26 (all four areas)
Anderson and Wise; as above.	0.25 (all four areas)
Vaughan and Huckins; Chicago.	0.6
Taylor et al; Southern Ontario.	0.5
AUSTRALIA	
Abelson; Sydney.	0.56 *
Holsman and Bradley; Sydney.	0.65 to 0.8 **

NOTE:

* Assuming the difference between a "noisy" and a "quiet" location is 10 dB(A), which is plausible.

** Approximations, based on the average yearly difference in mean house prices for main roads and parallel streets.

TABLE 3. NOISE INSULATION STAGES

STAGE OF INSULATION	INSULATION DETAILS	RANGE OF INCREMENTAL NOISE REDUCTIONS dB(A)	MEAN OR TYPICAL INCREMENTAL NOISE REDUCTION dB(A)
STAGE 1 Property line barrier	Barrier at property line. Height, metres	Compared with no barrier	
	2.0	6.3	8.3
	2.5	8.3	
	3.0	10.3	
STAGE 2 Facade	Leave front windows closed permanently. Install mechanical ventilation system for front rooms.	5 to 13	9.0
STAGE 3 Facade	Weather strip front door, and windows in front rooms. Plug any small cracks around window frames, skirtings, cornices and front door with a suitable filler or sealant.	1 to 4	2.5
STAGE 4 Facade	Upgrade front windows and fit solid-core front door with seals.	4 to 10	7.0
STAGE 5 Ceiling	Install thermal insulation in the ceiling.	4 to 8, for pitched roof.	6.0
STAGE 6 Facade	In front rooms glue battens 25 mm thick to existing plasterboard wall. Place 25 mm thick rockwool or fibreglass batts between battens and fix new plasterboard wall.	about 4	4.0

Stage 1: Property Line Barrier

Properly constructed, a property line barrier having a surface density of 15 kilograms per square metre will provide a useful reduction of traffic noise at the house facade (CSIRO, 1977). The noise reductions in Table 3 assume that kerb-to-property line and property line-to-facade distances are 4.1 and 7.6 metres respectively (Modra 1984, p 107). These distances are believed to be typical of many houses facing arterial roads.

Stage 2: Close Front Windows and Install Mechanical Ventilation

This stage is not identified explicitly either by the CSIRO or by the Wyle Research Laboratories yet it is clearly a low-cost option available to all householders. Modra (1984) discusses in some detail the basis for the 5 to 13 decibel range of noise reduction shown for this stage in Table 3. Mechanical ventilation for the front rooms has been included in this stage to avoid any possibility of stuffiness in these rooms. The duct work needs to be acoustically treated to prevent "leakage" of traffic noise into the house.

Stage 3: Weather Strip Front Windows and Door, and Seal Cracks

This stage aims to eliminate air leakage paths.

Stage 4: Upgrade Front Windows and Fit Solid-Core Front Door

The most common method of upgrading the acoustic performance of windows is to install double glazing with a suitable pane-to-pane spacing.

Stage 5: Install Thermal Insulation in the Ceiling

Provided materials such as fibreglass or rock wool are used, this stage introduces acoustic absorption into the roof space. Details of suitable materials are given by the CSIRO (1978).

Stage 6: Modifications to Interior Walls

This stage increases the mass of the interior walls and introduces sound absorbent material into the wall cavity.

Modra (1984) discusses at some considerable length the insulation details involved in each of these stages and the incremental noise reductions which can be expected to result from each. For present purposes, the information on noise reduction is summarised in Table 4.

It is important to observe that the six stages of insulation need not be undertaken in the order in which they are listed above: the areas of flexibility and constraint in their ordering follow from the general need (CSIRO 1978) to treat the front windows (and door) first, then the roof and then the walls (and finally, if appropriate, the floor), and are fully discussed by Modra (1984, pp 52-3). They may be summarised as follows:

(a) Stage 1 may be undertaken at any position in the order of sequence.

(b) Stages 3 and 4 each imply that the front door and windows normally will be kept closed, so that each of these stages must follow Stage 2 in which mechanical ventilation is installed. However, Stage 3 may precede Stage 4 or vice versa.

TABLE 4. NOISE REDUCTIONS DUE TO INSULATION STAGES

STAGE OF INSULATION	INCREMENTAL NOISE REDUCTION FOR STAGE, dB(A)	
	RANGE OF VALUES	MEAN/TYPICAL
1	6.3 - 10.3	8.3
2	5 - 13	9.0
3	1 - 4	2.5
4	4 - 10	7.0
5	4 - 8	6.0
6	4	4.0

(c) The ceiling insulation of Stage 5 will have no acoustic effect unless Stages 2, 3 and 4 have been completed; that is, from a noise reduction point of view, Stage 5 must be considered as being constrained to follow Stages 2, 3 and 4 (even in the case of a house already containing suitable ceiling insulation for thermal purposes).

(d) Stage 6 must follow Stage 5 because the acoustic effect of the wall treatment is not realised in the absence of ceiling insulation.

The combined effect of these precedence constraints is that there exist only two possible orderings of Stages 2, 3, 4, 5 and 6, namely 2-3-4-5-6 and 2-4-3-5-6; as Stage 1 can be added into each of these in any one of the six positions, a total of twelve feasible sequences of the stages is defined.

COSTS OF NOISE INSULATION STAGES

The basic source of cost data for each insulation stage was a number of quotations received from contractors for undertaking the work relevant to that stage at a particular property thought to be typical of houses situated on arterial roads in Melbourne. This house is on a building block 15.2 m (50 ft) wide, has three front rooms, seven double-hung sash windows on the front facade and 113.5 square metres (1222 square feet) of ceiling area. Specifications for work were prepared with the assistance of published information and verbal advice from CSIRO and acoustical consultants.

Given that only houses directly facing arterial roads are likely to be subjected to traffic noise levels sufficient to warrant treatment, the possible units in which cost data may be expressed include cost per kilometre of houses, cost per "block" of houses facing the arterial road and cost per house. Because all of the raw data was collected on a cost per house basis, this approach was adopted. In costing Stage 1 (timber barrier at property line) in which corner properties are treated differently from those at mid-block, an equivalent cost per house was derived assuming an average of six house blocks between consecutive minor streets.

For each of the noise insulation measures, there are two components of the total cost - the "first cost" incurred at the time of installation and a time stream of costs stemming from the maintenance, periodic replacement and, in one case, operation of the measure. Detailed consideration of the time streams of costs (Modra, 1984) indicates that they are negligible and that the total cost of each measure is sufficiently accurately represented by its first cost.

For each stage of insulation there is a range of cost estimates. Partly this range reflects the fact that some measures in any given stage are more effective than others and hence cost more (for example, a 3 metre high property line barrier, compared with one only 2 metres high). Partly, however, the range reflects the pricing strategies of different suppliers quoting on essentially the same product. A comprehensive discussion of the cost information which was collected for this project between September and November, 1983, was presented by Modra (1984), but for the purposes of the present paper the data is summarised in Table 5.

TABLE 5. SUMMARY OF COSTS OF INSULATION STAGES

STAGE	NUMBER OF QUOTATIONS	RANGE OF COSTS ($)	AVERAGE COST ($)
1	6(1)	1142 - 2408	1796
2	3(2)	630 - 900	793
3	3(2)	489 - 696	589
4	7(3)	730 - 1505	1249
5	9(4)	285 - 548	398
6	1	4248	4248

NOTES:

(1) One supplier, 6 alternatives (3 heights x 2 materials).
(2) Three suppliers, each quoting on similar work.
(3) Two suppliers, each quoting on several options.
(4) Four suppliers, each quoting on several options.

HOUSE PRICE FOR BENEFIT EVALUATION

Because the NDI expresses the benefit of noise reduction in terms of percentage increase in property value per dB(A) decrease in noise level, it is necessary to identify an appropriate property value to enable benefits to be expressed in dollar units. The derivations of NDI values discussed above used market price as the measure of property value, so that price is also the appropriate measure to use in analyses which apply the NDI.

It is recognised that in any given analysis it is the price of the particular housing in question which should be used to quantify benefits. However, for the purposes of enabling illustrative analyses to be undertaken and tentative conclusions to be drawn in this project, an average price of residential properties on arterial roads in Melbourne at the relevant time is estimated.

The Statewide Index (Statewide Building Society, 1984) indicates that in the second half of 1983 (when the costs to which benefits are to be compared were collected) the average price for a house and land in the Melbourne metropolitan area was $65,043. The Statewide Index is at present the only source available for the given period but because it has shown good agreement in the past with the Valuer General's property sales statistics for Victoria (eg the Statewide figure of $56,709 (Statewide Building Society, 1983) for the latter half of 1982, compared with $55,282 (Valuer General, 1983) for the whole of 1982, it is considered that the figure of approximately $65,000 for the second half of 1983 can be accepted as reasonable.

However, because of other, non-noise-related disutilities of living on arterial roads (eg visual impact of traffic, difficulty of driveway entry/exit), it may be appropriate to assume a lower average price for residential properties on arterial roads than for all residential properties. Bearing this in mind, an average house price of $60,000 is used in the subsequent illustrative analysis in this paper.

COST-BENEFIT ANALYSIS

Decision Criteria

In an unconstrained situation, standard cost-benefit theory would indicate that all those and only those stages of noise insulation for which the corresponding increment in benefit, ΔB, is not less than the corresponding increment in cost, ΔC, should be undertaken, i.e. those stages for which the incremental benefit-cost ratio, $\Delta B/\Delta C$, is greater than or equal to unity.

In the presence of either budgetary constraints or specified requirements for noise reduction, however, not all of those stages which satisfy the above criterion may be applied. Rather, the theory would indicate that the first stage of insulation applied should have the highest value of the ratio $\Delta B/\Delta C$ and that subsequent stages should be applied in decreasing order of this ratio until either a constraint forces a halt or there are no further stages for which $\Delta B/\Delta C$ is not less than 1.

This ordering of stages can be achieved using the parameter

$$S = \frac{\Delta NR}{\Delta C} \tag{1}$$

where ΔNR = increment in noise reduction for stage (dB(A)), and
ΔC = increment in cost for stage ($)

This is so because the increment in benefit, ΔB($), corresponding to any stage of noise insulation is given by

$$\Delta B = \frac{NDI}{100} \times HP \times \Delta NR \tag{2}$$

where NDI = noise depreciation index (%/dB(A)),
HP = house price ($)
and the other terms are as already defined.

That is,

$$\Delta B = \text{constant} \times \Delta NR \tag{3}$$

for a given NDI and house price.

The parameter S can be interpreted as the slope of a line segment corresponding to a particular stage of insulation in a plot of cumulative noise reduction against cumulative treatment cost (i.e. an incremental effectiveness-cost ratio).

The application of the above criteria, however, is complicated by the stage precedence constraints which were discussed earlier, as is shown in the following section.

Analysis of Base Case

The first cost-benefit analysis is that of the "Base Case" for which the NDI value of 0.5%/dB(A), the mean or typical incremental noise reductions listed in Table 4, the average treatment costs from Table 5 and an average house price of $60,000 are assumed.

From the incremental noise reductions and treatment costs, the values of the parameter S listed in Table 6 can be calculated for the various insulation stages. These show that arrangement of the stages in order of decreasing value of S would produce the sequence (with S-values in parentheses) Stage 5 (15.08), Stage 2 (11.35), Stage 4 (5.60), Stage 1 (4.62), Stage 3 (4.24) and Stage 6 (0.94). However, this order is infeasible because it does not satisfy the stage precedence constraints which, it will be recalled, permit the stages excluding Stage 1 to be undertaken only in one of the two orders 2-3-4-5-6 or 2-4-3-5-6, into either of which Stage 1 may be added in any position.

TABLE 6. S-VALUES FOR INSULATION STAGES

STAGE OF INSULATION	INCREMENTAL NOISE REDUCTION ΔNR (dB(A))	INCREMENTAL COST ΔC ($)	$S = \frac{\Delta NR}{\Delta C}$ dB(A)/$1000
1	8.3	1796	4.62
2	9.0	793	11.35
3	2.5	589	4.24
4	7.0	1249	5.60
5	6.0	398	15.08
6	4.0	4248	0.94

The sequence of actions producing any given level of noise reduction at minimum cost (and also the maximum noise reduction for any given cost) subject to the precedence constraints can be identified if "actions" are defined to include combinations of insulation stages as well as individual stages. The considerations which identify this sequence of actions are as follows:

(a) Stage 2 must be undertaken first because it must precede or be included in all other actions except Stage 1, which has a lower S-value;

(b) Stage 4 must be next because it must precede or be included in all other actions except Stage 1 and Stage 3, each of which has a lower S-value than Stage 4;

(c) the combination "Stage 3 plus Stage 5" must be next because it must precede Stage 6 and has a higher S-value (8.61) than Stage 1; and

(d) Stage 1 must be second-last and Stage 6 last because Stage 1 has the higher S-value of the two.

The optimal sequence of stages is thus 2-4-3-5-1-6 and its interpretation as a plot of cumulative noise reduction against cumulative treatment cost is shown in Figure 2. As the broken lines on this diagram indicate, however, it is possible that for some values of NDI and house price, an action which is a combination of stages may be justified even though one or more of the Stages comprising that action may not be individually justified. For example, the combination of Stages 4, 3 and 5 has a greater S-value than either Stage 4 or Stage 3 individually, and hence also has a greater incremental benefit-cost ratio (for given NDI and house price) because it follows from equations (1) and (2) above that the incremental benefit-cost ratio corresponding to any noise insulation action is

$$\frac{\Delta B}{\Delta C} = \frac{NDI}{100} \times HP \times S \qquad (4)$$

A further qualification which must be noted for the optimal sequence derived above arises because of the discrete nature of possible actions and has relevance in the presence of budgetary or performance constraints. Where such constraints apply, it is possible, for certain constraint levels, that where two alternative actions are being considered as the next to be implemented, that with the lower S-value may be chosen because it fits within the budget (or performance) constraint whereas the other action does not. In the present context, two examples arise of action sequences which are not part of the optimal sequence 2-4-3-5-1-6 : the sequence 2-3 produces the maximum achievable noise reduction for a budget, B, in the range $\$1382 \leqslant B < \$2042$ and also is the least-cost means of obtaining a noise reduction, NR, in the range 9.0 dB(A) < NR ⩽ 11.5 db(A); the second case is the sequence 2-1 which is optimal for a budget in the very narrow range $\$2589 \leqslant B < \$2631$ or for a minimum required noise reduction in the range 16.0 dB(A) < NR ⩽ 17.3 dB(A). For all other ranges of budgetary or performance constraints, the optimal sequence of actions is part of the sequence 2-4-3-5-1-6 which was defined by maximum S-values. These results are summarised in Table 7 in any row of which the sequence of actions shown in the centre column is optimal for the budget range in the left column and for the range of required noise reductions in the right column. The actual cost of each sequence of actions is of course the lower limit of its budget range and the actual noise reduction produced is the upper limit of the noise reduction range.

The question of which insulation stages are economically justified depends on the incremental benefit-cost ratio, $\Delta B/\Delta C$, which can be evaluated using equation (4). Any stage for which this ratio is not less than unity is justified.

It follows from equation (4) that for the "Base Case" assumptions of NDI = 0.5%/dB(A) and HP = \$60,000 (leading to NDI/100 x HP = \$300/dB(A)), that an insulation stage is economically justified provided that its S-value is greater than or equal to 3.33 dB(A)/\$1000. Comparing the values in Table 6 with this criterion it is seen that all stages except Stage 6 are justified.

In summary, for the "Base Case" in the presence of budgetary or performance constraints, insulation stages should (with the minor exceptions noted) be undertaken in the order : Stage 2 (close front windows and install ventilation system), Stage 4 (upgrade front windows and door), Stage 3 (weather strip front windows and door, seal cracks), Stage 5 (thermal insulation in ceiling) and finally, Stage 1 (property line barrier). All

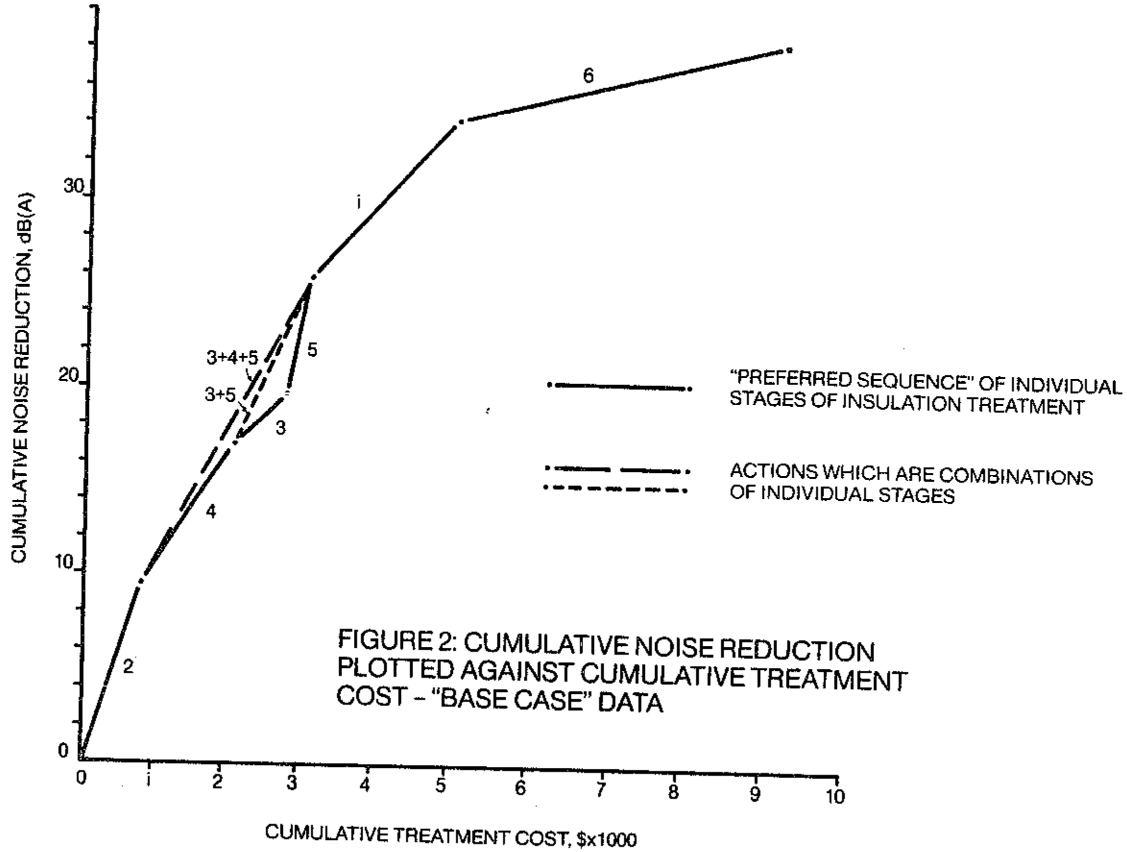


FIGURE 2: CUMULATIVE NOISE REDUCTION PLOTTED AGAINST CUMULATIVE TREATMENT COST – "BASE CASE" DATA

these five stages are economically justified and, in the absence of budgetary constraints, should be undertaken. Stage 6 (modify interior walls) is not economically justified.

TABLE 7. OPTIMAL NOISE INSULATION MEASURES UNDER BUDGETARY OR PERFORMANCE CONSTRAINTS

RANGE OF BUDGET ($)	OPTIMAL SEQUENCE OF STAGES	RANGE OF REQUIRED NOISE REDUCTION (dB(A))
$0 \leq B < 793$	None feasible	NR = 0
$793 \leq B < 1382$	2	$0.0 < NR \leq 9.0$
$1382 \leq B < 2042$	2-3	$9.0 < NR \leq 11.5$
$2042 \leq B < 2589$	2-4	$11.5 < NR \leq 16.0$
$2589 \leq B < 2631$	2-1	$16.0 < NR \leq 17.3$
$2631 \leq B < 3029$	2-4-3	$17.3 < NR \leq 18.5$
$3029 \leq B < 4825$	2-4-3-5	$18.5 < NR \leq 24.5$
$4825 \leq B < 9073$	2-4-3-5-1	$24.5 < NR \leq 32.8$
$9073 \leq B$	2-4-3-5-1-6*	$32.8 < NR \leq 36.8$

* Note, however, that Stage 6 is not economically justified for the "Base Case".

Sensitivity Analyses

The above cost-benefit analysis of the "Base Case" has utilised what are considered to be best estimates of NDI, house price and the effectiveness and costs of insulation treatments as inputs to the calculation of incremental benefit-cost ratios using equations (1) and (4). It is now appropriate to examine the robustness of the results obtained by considering their sensitivity to variations in the inputs. In this respect, there are two principal issues to be addressed:

(a) possible variations in the preferred order of implementation of insulation stages; and

(b) possible changes in the economic justification (or lack thereof) of insulation stages or actions.

The first of these issues is primarily dependent upon the S-values of insulation stages or actions because the assumption is made that the same NDI value and house price are used in calculating all incremental benefit-cost ratios using equation (4) (note, however, that a possible qualification of this assumption in relation to one insulation stage is considered below). To assist discussion, the S-values of all insulation stages and relevant actions (stage combinations) are listed in column 2 of Table 8.

Given the stage precedence constraints, the only questions of implementation order which arise are, firstly, which of Stages 3 and 4 should

TABLE 8. DATA FOR SENSITIVITY ANALYSES

(1) INSULATION STAGE OR ACTION	(2) $S = \frac{\Delta NR}{\Delta C}$ dB(A)/$1000	(3) INCREMENTAL BENEFIT-COST RATIO $\Delta B / \Delta C$	(4) % CHANGE TO GIVE $\Delta B / \Delta C = 1$	(5) BREAK-EVEN NDI %/dB(A)
2	11.35	3.40	- 71	0.147
4	5.60	1.68	- 41	0.297
3	4.24	1.27	- 27	0.393
5	15.08	4.52	- 78	0.111
3 + 5	8.61	2.58	- 61	0.194
4 + 3 + 5	6.93	2.08	- 52	0.240
1	4.62	1.39	- 28	0.361
6	0.94	0.28	+254	1.770

be undertaken first and, secondly, at what point Stage 1 should be undertaken.

Table 8 shows that the S-value for Stage 3 (4.24) is 24% less than that for Stage 4 (5.60). This difference is not large in view of the possible variations in noise reductions and costs for the two stages shown in Tables 4 and 5. However, even though it is not brought out in the summary information presented in this paper, there is a general positive correlation between noise reduction effectiveness and cost for each of these stages (Modra, 1984), so that while the ranges of variation of ΔNR and ΔC may be quite large, the range of variation of their quotient, S, may not be as large. Nevertheless, it would appear possible that in some situations Stage 3 might precede Stage 4 rather than the reverse.

The position of Stage 1 (property line barrier) in the implementation sequence may be assessed by comparing its S-value (4.24) with that of the combined action Stages 3+4+5 (6.93) and with that of Stage 2 (11.35). Again, for Stage 1 there is a strong positive correlation between effectiveness and cost, with higher barriers both costing more and being more effective. In addition, the range of costs listed for Stage 1 in Table 5 is large because quotations for two different materials - ordinary builders' hardwood (OBH) and pressure treated pine (PTP) - are included, with the latter producing prices 50% to 80% more than the former. An examination of all barrier options shows that the lowest S-value is 3.07 for a 2 m-high PTP barrier and the highest is 6.50 for a 3 m-high OBH barrier. This highest value is still below the best-estimate S-value for action 3+4+5, but it is close, and a reduction in the latter value due to effectiveness and/or cost variations may see Stage 1 being preferred in some situations. It seems unlikely, however, that there would be justification for Stage 1 to precede Stage 2 on the basis of S-value variations.

A second issue in relation to Stage 1 arises from the fact that it is the only insulation measure implemented externally. Unlike the other stages, the property line barrier will reduce noise levels in the front and backyards of a property, not only within the house. Hence it may be considered reasonable to apply a higher NDI value to the expected interior noise level reduction for Stage 1 than for the other stages, in order to reflect the additional benefit of noise reduction in the external parts of the property. If this is so, then it is quite likely that Stage 1 should be implemented prior to action 3+4+5, especially if the less costly OBH barrier construction is used, as this would require the NDI appropriate for Stage 1 to be only a little larger than that applicable to the other stages (e.g. as little as 7% larger if a 3 m OBH barrier is built). In order to justify the implementation of Stage 1 prior to Stage 2 the NDI value applied to Stage 1 would need to be of the order of twice that applicable to other stages. Further research is necessary to determine whether this is likely.

The second sensitivity question - that of the economic justification of insulation stages and actions - also is addressed by Table 8. Column 3 of this table lists incremental benefit-cost ratios for each measure for the "Base Case" and column 4 shows the percentage changes required to reduce (or, in the case of Stage 6, to increase) the ratio to unity. It is clear that the source of such changes could be any or all of the variables which are inputs to calculation of the benefit-cost ratio, that is, NDI, house price and effectiveness and costs of noise insulation measures (or S-values).

The possible error in the assumption of $60,000 as an average house price at the relevant time probably is much smaller than that required to alter the economic justification of any measures, given the "Base Case" NDI and

S-values. To render Stage 1 uneconomic, for example, would require a house price below $44,000 for the "Base Case" S-value, or below $31,000 if a 3 m OBH barrier is built in Stage 1. Conversely, a house price in excess of $200,000 would be necessary to justify Stage 6.

The variation of S-values already has been discussed in the context of the first sensitivity question. On the basis of that discussion it may be concluded that although significant variations from the 'best estimate' S-values are possible, such variations alone are unlikely to alter the economic justification of any insulation measure.

The influence of assumed NDI value is addressed by column 5 of Table 8 which lists the "break-even NDI" for each measure, that is, the NDI which would produce an incremental benefit-cost ratio of unity given the "Base Case" house price and S-value. Comparison of these with the range of empirically-derived NDI values of 0.25 to 0.80 in Table 2 indicates that Stage 2 and action 4+3+5, having breakeven NDI values below 0.25, are likely to remain justified, while Stage 6, with a breakeven NDI more than twice the upper limit of 0.80 is most unlikely ever to be justified. Stage 1 has a breakeven NDI of 0.36 for the "Base Case" S-value (0.26 for a 3 m OBH barrier) and is likely to remain justified, particularly if the arguments supporting the appropriateness of a higher NDI for this measure are accepted.

It is recognised, of course, that if all variables simultaneously have values toward the unfavourable ends of their ranges (i.e. low values of NDI, HP and ΔNR with a high value of ΔC), then the deviation of each from its best-estimate value need not be so great in order to remove the economic justification for an insulation measure. Nevertheless, the results are considered sufficiently robust to conclude that, in general, all insulation stages except Stage 6 are likely to be economically justified.

CONCLUSIONS

This paper has presented a cost-benefit analysis of the application of traffic noise insulation measures to existing houses.

To estimate benefits, the analysis has employed a Noise Depreciation Index (NDI) which identifies the percentage increase in the price of a residential property which can be ascribed to a one decibel decrease in interior noise level. On the basis of Australian and overseas studies, the range of likely values of NDI was identified as 0.25 to 0.80%/dB(A) and a best-estimate value of 0.5%/dB(A) was used in the analysis. Examination of property sales data for the relevant period indicated that the average house price to which the NDI should be applied could be taken to be $60,000.

A detailed survey of noise insulation measures which could be applied to existing houses culminated in the identification of six "insulation stages" to be considered in the analysis. These were: Stage 1 - installation of a property line barrier; Stage 2 - closure of front windows and installation of a ventilation system; Stage 3 - weather stripping of front windows and door, sealing cracks; Stage 4 - upgrading front windows and door; Stage 5 - installation of ceiling insulation; and Stage 6 - modification of interior walls. The survey included collection of data on the noise reduction effectiveness of each stage, constraints on the order in which the stages could be undertaken and the costs of implementation of each stage.

Analysis of a "Base Case" which utilised best-estimate values of the input variables, indicated that all insulation stages with the exception of

Stage 6 were likely to be economically justified. Sensitivity analyses examined this finding in the light of possible variations in the values of inputs to the cost-benefit calculations and concluded that it was likely to be valid in most situations.

Because the application of traffic noise insulation treatment to houses would be expected to be undertaken under budgetary constraints and/or constraints on the required level of noise reduction, so that not all of the economically justified measures may be applied, a "preferred sequence" of insulation stages (influenced also by the constraints on the ordering of stages) was identified. In general, this sequence was: Stage 2 (close front windows, install ventilation), Stage 4 (upgrade front windows and door), Stage 3 (weather strip windows and door, seal cracks), Stage 5 (ceiling insulation) and finally, Stage 1 (property line barrier); two minor variations from this sequence, consequent upon the discreteness of the stages, were noted. Sensitivity analyses of the sequencing of stages revealed that the findings were relatively robust; however, it was found to be quite likely that the order of Stages 4 and 3 could be reversed in some situations and that the implementation of Stage 1 prior to the combination of Stages 4, 3 and 5 could prove more effective in some cases.

A need was identified for further research into the appropriateness of applying higher NDI values to insulation measures, such as property line barriers, which reduce exterior as well as interior noise levels.

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MODELLING EMISSIONS FROM CARS

H.C. Watson
Department of Mechanical & Industrial Engineering
University of Melbourne

E.E. Milkins
Department of Mechanical & Industrial Engineering
University of Melbourne

P.A. Holyoake
Department of Mechanical & Industrial Engineering
University of Melbourne

E.T. Khatib
Department of Mechanical & Industrial Engineering
University of Melbourne

S. Kumar
Department of Mechanical & Industrial Engineering
University of Melbourne

ABSTRACT:

Exhaust emissions, HC, CO and NO_x are identified as being more variable than fuel consumption, and therefore more difficult to model. The causes of variability in both source and measurement are described. The emissions rates and their coefficients of variation are depicted on joint axes of power and speed which allow explanation of the terms in 5 models of the lumped parameter type. Four cars have been selected to test the models. The performance of the models in 'closed loop' tests tends to improve with increasing complexity. Generally, emissions are predicted with 2 to 5 times the errors experienced in the prediction of fuel consumption with a given level of model.