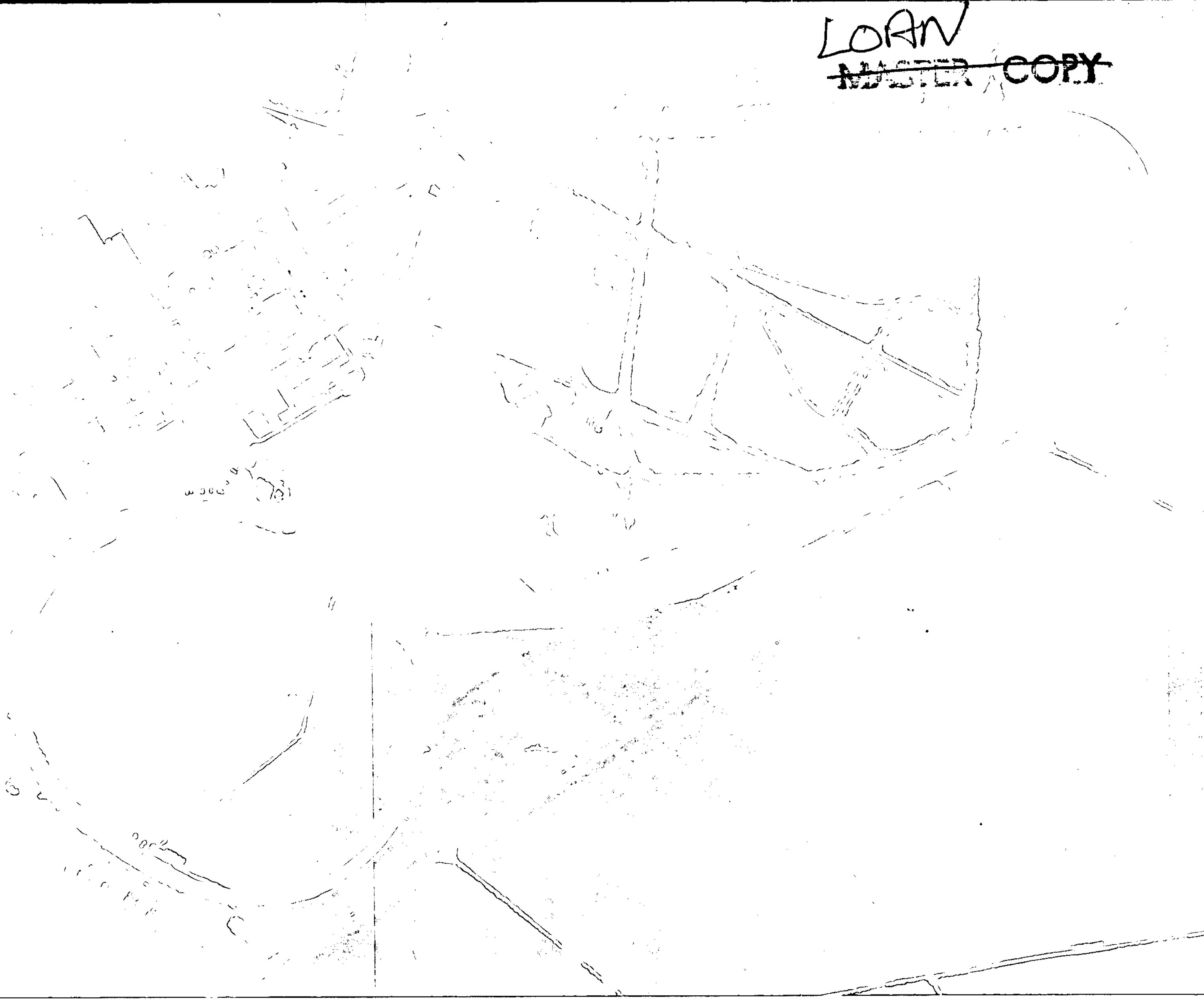
TRRL Laboratory Report 667

TRANSPORT and ROAD
RESEARCH LABORATORY
DEPARTMENT of the ENVIRONMENT



Risk and the pavement design decision in developing countries

by

C. I. Ellis

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**Overseas Unit
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ABSTRACT

In this report the principles of simple decision analysis are applied to road pavement design in developing countries and the uncertainties in the pavement design process are described. Decision analysis is seen as providing a framework within which 'engineering judgement' may be exercised by the placing of subjective probabilities on the possible outcomes resulting from the use of different designs. It is proposed that pavement design should be considered not so much in terms of 'success' or 'failure' but more in terms of a satisfactory return on the investment of highway funds. In this way decisions may be based on an assessment of both technical and financial risks.

1. INTRODUCTION

In common with most engineering decisions there is a risk element in decisions about pavement design. The purpose of this Report is to put forward an ordered way of thinking about the pavement design decision to help the highway engineer and his client to choose the most reasonable course of action under the conditions of risk or uncertainty known to him at the time.

Whilst not normally applied to highway engineering, the decision analysis approach is often used to advantage in the consideration of business decisions[1]. Therefore, since the pavement design decision cannot be divorced from decisions about long-term financial investment, it seems appropriate that decision analysis should be considered in this context. This Report illustrates the use of the decision analysis approach in connection with pavement design, by means of simple examples showing the principles involved. For more detailed information on its use on specific engineering topics the reader is referred to Benjamin and Cornell[2], Burton and Walker[3], and Wu[4].

Any engineering decision which involves uncertainty provides an opportunity for the use of 'engineering judgement': that indefinable quality possessed by the professional engineer as a result of all his previous experience. Decision analysis provides a framework within which engineers can exercise judgement in their own specialist field and hence avoid the unnecessary expenditure which may result from a too rigid adherence to general specifications which may not be totally applicable to a particular project. Decision theory, as applied to pavement design in this Report, provides a way of using 'engineering judgement' more effectively. It does not replace this judgement.

This Report has been written with a view to its particular application in developing countries where the scope for substantial savings on project costs is known to be large. However, it is believed that the techniques described will also find application in developed countries.

2. THE PAVEMENT DESIGN PROCESS

Modern methods for the thickness design of road pavements take account of three main factors:

1. Traffic
2. Subgrade strength
3. Pavement materials

The elements of uncertainty in all three factors are discussed below.

2.1 Traffic

For pavement design purposes details are required of the commercial vehicles likely to use the road during the design life of the road. In the TRRL design methods[5, 6], the traffic is expressed in terms of a cumulative number of equivalent standard axles; this requires a knowledge of the following:

a) present or initial flow of commercial vehicles
b) future growth of commercial vehicle traffic
c) axle-load distribution of commercial vehicles during the economic life of the road
d) relative damaging effects of different axle loads.

An estimate of the initial flow of commercial vehicles is usually based on traffic surveys on the existing route between the end points of the new project. On an existing route, there will be errors in estimating the present average daily flow of commercial vehicles, resulting from the counting methods used to obtain the data. Work by TRRL in Kenya[7] suggests that estimated daily traffic flows can rarely be expected to be better than ±30 per cent of the true value averaged over the whole year. Although repeating counts at intervals throughout the year increases the accuracy of traffic estimates, this is achieved only at a disproportionate increase in cost. For new routes there is the additional problem of estimating generated, diverted or redistributed traffic.

Estimation of future growth is also difficult and Howe[8] has suggested that, although it is impossible to state precisely what the magnitude of the errors in estimating the future growth of commercial vehicles will be, a minimum confidence interval of ±50 per cent seems likely. Howe therefore concludes that estimates of the cumulative number of commercial axles are subject to confidence intervals of the order of ±100 per cent.

The axle-load distribution of commercial axles can only be determined accurately from axle-load surveys. Most designers assume that the axle-load distribution as initially determined will remain constant with time. This is certainly not the case at present in many developing countries where vehicle operators are taking advantage of larger vehicles and the difficulties of enforcing vehicle weight regulations, with a resultant steady increase in axle-loads. In addition, in many cases a new road is built to exploit development potential of a new kind and the vehicles which will use the new facility will probably be of different types from those previously using roads in the vicinity.

There is also an element of uncertainty in the validity of the equivalence factors used to relate axle-loads to the damaging effect of an equivalent standard axle (ESA). Whilst the factors quoted in TRRL design methods are believed to be the most appropriate in the light of up-to-date research, they are not necessarily equally applicable to all conditions.

Having pointed out these limitations of the traffic estimating procedures, it is important to realise that in fact the pavement construction costs for new roads are relatively insensitive to small variations in traffic estimates, especially for pavements on the stronger subgrades. For example, for subgrade CBRs between 8 per cent and 24 per cent, Road Note No 31[6] recommends only an extra 50 mm of base thickness for a fifty-fold increase in traffic from say 0.05×10^6 repetitions to 2.5×10^6 repetitions of ESAs. This extra thickness may increase the pavement cost by about 15 per cent and the total road construction cost by as little as 5 per cent for a typical surface-dressed road, i.e., a 1 per cent increase in total costs for each ten-fold increase in traffic. For pavements on weaker subgrades, however, the cost increase would be greater.

On the other hand, pavement life is measured in terms of traffic (i.e. ESAs). Therefore 'life' and pavement maintenance costs are much more sensitive to errors in traffic estimates.

2.2 Subgrade strength

Estimates of subgrade strength are based on a knowledge of the soil type and how that soil reacts to changes in moisture content in a particular climatic environment and to compaction. From this knowledge an estimate is made of subgrade strength related to the moisture content and compaction state likely to pertain in the field. This is normally in the form of a CBR value at a specified level of compaction and equilibrium moisture content, as described in RN 31[6].

Various methods are available for estimating the equilibrium moisture content[6]. Errors are likely as a result of variability of the soil and in the assessment of relevant environmental conditions, eg depth to water-table.

The degree of compaction achieved may also cause differences in the actual field density achieved during construction. These errors may be as a result of the level of supervision, the moisture content at the time of compaction or merely the differences between field and laboratory compaction techniques. The sensitivity of CBR values to these variables is best demonstrated by means of an ISO-CBR chart of which Fig. 1 is an example. Since differences in estimated CBR values mainly affect the thickness of the cheaper sub-base materials, the effect of such uncertainties is likely to be less than 20 per cent of pavement costs.

2.3 Pavement materials

The selection of pavement materials is probably the aspect of pavement design where the biggest financial savings can be made in developing countries. This is because there is often a large difference in cost between a material that would probably be suitable and a material that would definitely be suitable.

The decision maker should ask himself three questions:

1. Is the specification appropriate for the particular circumstances?
2. Does the material satisfy the specification for the pavement layer in question?
3. How much weight should be attached to the performance of alternative materials in similar circumstances?

The first question highlights the problem of choosing the correct specification and making sure that individual clauses of a specification are valid for a particular project. Perhaps the most obvious example of incorrect choice is the use in tropical areas of specifications written for temperate climates, with the possible result that a material may be rejected for use in a tropical country because it fails a strength criterion devised for an area in which frost has a serious effect. In general, practical cases will not be so clear cut.

The uncertainty in the answer to the second question ("does the material satisfy the specification?") lies in the identification of the conditions quoted in the specification: ie "what is the equilibrium moisture content?" or "What dry density corresponds to 95 per cent Mod AASHO compaction".

Perhaps the most difficult situation for the designer is that in which an unprocessed natural material (B) fails to meet a specification but local experience suggests that it will be adequate. Should he use the cheap natural material or spend perhaps three times as much producing another material (A) to specification? Not unnaturally the designer will often choose the expensive material so that he can use the specification in his defence should problems subsequently arise.

2.4 Courses of action

The possible courses of action in the design process may be represented on a diagram, as shown in Fig. 2. For the purpose of this diagram, only two alternatives have been considered at each stage of the design process, ie

a) the design traffic is estimated to be either 1.0 x 10^6 ESA or 0.5 x 10^6 ESA
b) the design CBR of the subgrade is either 4 per cent or 7 per cent
c) use is made of either material A which meets the standard specification or material B which does not.

This gives the designer a choice of eight possible courses of action. In practice there may well be more than two alternatives at any stage.

The purpose of this brief review of some aspects of the pavement design process has been to illustrate the uncertainties involved.

3. FAILURE CRITERIA

Failure is an emotive word which conjures up an image of poor quality and bad workmanship, attended by disastrous consequences such as the total collapse of a bridge or a dam, with severe loss of life or property. For this reason, quite rightly in many cases, failure is seen as something which must be avoided.

However, to a road designer, 'failure' is usually associated with an arbitrary 'standard', defined in terms of cracking and deformation of the new surfacing. Road 'failures' seldom result in a road being unusable by vehicles and rarely have disastrous economic or social consequences. Therefore, perhaps it is appropriate to see the pavement design decision not so much in terms of 'success' or 'failure', but more in terms of a satisfactory return on the investment of highway funds. Decisions are thus based on an assessment of both technical and financial risks.

4. DECISION ANALYSIS

4.1 Decision criteria

In a decision between two alternative designs, for example between A_1 and A_2 in Fig. 2, there are two possible outcomes to each choice. The resulting road may either 'fail' or not 'fail'. In the event of 'failure' the cost of rehabilitation must be borne; the cost of restoring the more expensive alternative would usually be less than the cost of restoring the cheaper design. We may distinguish between the 'satisfactory' cost of a design, ie the construction cost, and the 'unsatisfactory' cost, ie construction cost plus restoration cost. Table 1 shows an example of this. In the case of the cheaper design the figure for restoration cost (£1.5 mil) is taken as equivalent to the construction cost for the more expensive design.

TABLE 1

Example of possible outcomes of design decision

Decision	Outcome	
	Satisfactory	Unsatisfactory
	£ mil	£ mil
Build design A_1	1.5	1.5 + 0.5 = 2.0
Build design A_2	1.0	1.0 + 1.5 = 2.5

A possible criterion for choosing between the two designs is to select the design for which the worst outcome is the least expensive. This is usually called the 'minimax loss' approach[1] (ie minimum maximum loss) and is implemented by choosing that action for which the maximum possible cost is minimised. It is a very conservative approach since it assumes that whatever decision is made, the road will fail and require strengthening.

The 'unsatisfactory' costs in Table 1 are then the maximum possible costs of the two designs and clearly the lowest maximum cost is that associated with design A_1 which is then the correct choice based on this criterion.

ie From the example in Table 1:
the maximum possible cost of building design A_1 is £2.0 million
the maximum possible cost of building design A_2 is £2.5 million
∴ the lowest maximum cost is £2.0 million
∴ using this criterion we choose the design A_1

This illustrates that the use of this criterion tends to avoid the worst outcomes but takes no account of opportunities for reducing costs or the probabilities of a particular outcome occurring.

4.2 Decision trees

If we consider the situation in Table 1, the basic problem may be represented in the form of a simple decision tree (see Fig. 3). Up to now, no account has been taken of the probabilities of the different outcomes occurring as a result of a particular design decision. However, in practice, an engineer faced with a similar problem would, as a result of his experience, be able to make a judgement on the relative merits of the two designs. He may say something like. . . "I think both designs would probably be satisfactory but Design A_1 is less likely to fail than Design A_2". From this statement it is only a short step to putting numerical values to his judgement: for example . . ."I think there's a 90 per cent chance of Design A_1 being satisfactory". In so doing, he has assigned personal probabilities to the likely outcome of his actions and these are normally expressed on a scale 0 to 1. Hence a 70 per cent chance of Design A_2 being satisfactory may be expressed as a probability of 0.7 and consequently a 0.3 probability (1.0 – 0.7) of it not being satisfactory. In this way we can return to our simple decision tree and insert our estimated probabilities (Fig. 4). An engineer's judgement will reflect his experience; so will his probability assignments. However, experienced engineers, given the same information, will tend to make similar probability assignments.

For our basic problem (Fig. 4) we have placed a monetary value at the end of each branch of the decision tree. In this case the monetary value is the estimated total cost of any particular outcome. By multiplying a monetary value by its probability of occurrence, we can calculate the 'expected monetary value' of a design (in this case the 'expected cost'). Thus, using the probabilities given in Fig. 4, we have

Expected cost of design A_1

$(0.1 \times 2.0) + (0.9 \times 1.5) = 0.20 + 1.35 = £1.55$ mil

Expected cost of design A_2

$(0.3 \times 2.5) + (0.7 \times 1.0) = 0.75 + 0.7 = £1.45$ mil

Thus, if we use minimum 'expected cost' as our decision criterion, we would now choose design A_2.

Normally there is a range of possible outcomes for the two selected designs A_1 and A_2. The example below shows how these can be considered.

For each decision the basic outcome is still as before, ie either the road will be satisfactory or it will be unsatisfactory and therefore will require strengthening. However, if strengthening is required, there is a further range of possible outcomes to be considered. The strengthening layer will have to be designed on the basis of measurements of the residual strength of the pavement at the time. For simplicity, let us assume there are two, and only two, possible outcomes: either a 50 mm or a 100 mm layer of bituminous overlay. It is estimated that the probability of a 50 mm layer being required is 0.7 and hence, since we have assumed only two possible outcomes, there is a 0.3 probability of a 100 mm layer being required. We will also consider the probability of whether each of these overlays will subsequently be satisfactory or not. The full decision tree is given in Fig. 5 and an alternative form of the tree is given in Fig. 6.

4.3 Discounted costs

The expected costs used as a criterion may be actual costs or discounted costs. In most pavement performance situations, the time interval between initial construction and subsequent pavement strengthening is large, and therefore discounted costs have been considered in our example. Table 2(a) gives example costs/km for each of the ten possible outcomes considered in Figs. 5 and 6, and Table 2(b) gives these costs discounted at a rate of 10 per cent for a 20-year design life.

If the discounted costs of each possible outcome of a particular design are multiplied by the corresponding probability and then added together, we obtain the expected discounted cost.

TABLE 2(a)

Decision tree costs

Years	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0	18500	18500	18500	18500	18500	14000	14000	14000	14000	14000
1										
2										
3										
4										
5								9000†	9000†	
6						4500*	4500*			
7										
8										
9										
10	4500*	4500*								
11										
12										
13			9000†	9000†						
14										
15						4500*				
16										
17	4500*									
18								4500*		
19										
20			4500*							
Total Costs (£)	27500	23000	32000	27500	18500	23000	18500	27500	23000	14000

* 50mm overlay

† 100mm overlay

TABLE 2(b)

Decision tree discounted costs – 10 per cent discount rate

Discount Factor	Years	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0	0	18500	18500	18500	18500	18500	14000	14000	14000	14000	14000
0.90909	1										
0.82644	2										
0.75131	3										
0.68301	4										
0.62092	5								5588	5588	
0.56447	6						2540	2540			
0.51315	7										
0.46650	8										
0.42409	9										
0.38554	10	1735	1735								
0.35049	11										
0.31863	12										
0.28966	13			2607	2607						
0.26333	14										
0.23939	15						1077				
0.21762	16										
0.19784	17	890									
0.17985	18								810		
0.16350	19										
0.14864	20			669							
Total Discounted Costs (£)		21125	20235	21776	21107	18500	17617	16540	20398	19588	14000

Thus the expected discounted cost per km for a decision to use design A_1 is:

(£21 125 x 0.0018) + (£20 235 x 0.0882) + (£21 776 x 0.0) + (£21 107 x 0.010) + (£18 500 x 0.90)

= £(38 + 1785 + 0 + 211 + 16 650)

= £18 684 per km

The expected discounted cost per km for a decision to use design A_2 is:

(£17 617 x 0.021) + (£16 540 x 0.189) + (£20 398 x 0.0018) + (£19 588 x 0.0882) + (£14 000 x 0.70)

= £(370 + 3126 + 37 + 1728 + 9800)

= £15 061 per km

4.4 Interpretation

The least expected discounted cost is thus £15 061 per km. Therefore, if least expected discounted costs are accepted as a valid criterion, we decide to use Design A_2. This does not mean that if we choose A_2 the actual discounted cost will be £15 061 per km. It could have any of the values C_6 to C_{10} in Table 2(b). However, Table 3 shows the probability of its having a particular value. An alternative method of presenting the same information is given in Table 4.

TABLE 3

Expected costs

a) Probability of a given discounted cost, design A_1

90 per cent chance of scheme being satisfactory for a discounted cost of £18 500 per km
8.82 per cent chance of scheme being satisfactory for a discounted cost of £20 235 per km
1.0 per cent chance of scheme being satisfactory for a discounted cost of £21 107 per km
0.18 per cent chance of scheme being satisfactory for a discounted cost of £21 125 per km
0 per cent chance of scheme being satisfactory for a discounted cost of £21 776 per km

b) Probability of a given discounted cost, design A_2

70 per cent chance of scheme being satisfactory for a discounted cost of £14 000 per km
18.9 per cent chance of scheme being satisfactory for a discounted cost of £16 540 per km
2.1 per cent chance of scheme being satisfactory for a discounted cost of £17 617 per km
8.82 per cent chance of scheme being satisfactory for a discounted cost of £19 588 per km
0.18 per cent chance of scheme being satisfactory for a discounted cost of £20 398 per km

TABLE 4

Expected costs (alternative presentation)

a) Probability of a given discounted cost, design A_1

90 per cent chance of scheme being satisfactory for discounted cost of £18 500 per km
98.82 per cent chance of scheme being satisfactory for discounted cost of £20 235 or less per km
99.82 per cent chance of scheme being satisfactory for discounted cost of £21 107 or less per km
100 per cent chance of scheme being satisfactory for discounted cost of £21 125 or less per km

b) Probability of a given discounted cost, design A_2

70 per cent chance of scheme being satisfactory for discounted cost of £14 000 per km
88.9 per cent chance of scheme being satisfactory for discounted cost of £16 540 or less per km
91.0 per cent chance of scheme being satisfactory for discounted cost of £17 617 or less per km
99.82 per cent chance of scheme being satisfactory for discounted cost of £19 588 or less per km
100 per cent chance of scheme being satisfactory for discounted cost of £20 398 or less per km

Expected costs are not always an accurate indicator of a decision maker's feelings about a situation. This is particularly true where possible losses or gains are large compared with the decision maker's resources. In the pavement design situation this may arise, for instance, where the possible extreme values are widely different from the expected value.

For example, consider two possible extreme cases:

Case 1 There is a 0.75 probability of total cost being £1 mil but, owing to the use of a marginal base material, there is a 0.25 probability of total cost being £10 mil, where the additional £9 mil is reconstruction and extra maintenance costs.
Expected cost = (0.75 x 1) + (0.25 x 10) = 0.75 + 2.5
= £3.25 mil

Case 2 There is 0.50 probability of total cost being £3.5 mil
and 0.50 probability of total cost being £5.0 mil
Expected cost = (0.50 x 3.5) + (0.5 x 5.0) = 1.75 + 2.5
= £4.25 mil

Using the least expected cost as a criterion, the decision would be made in favour of Case 1. However, the decision maker may feel that he is not prepared to take the risk of Case 1 costing £5 mil more than the maximum possible cost of Case 2.

On the other hand, if the decision maker is responsible for a very large road maintenance organisation with an annual budget which is very large relative to the possible £9 mil additional expenditure, he may be prepared to accept the risk and make his decision on the basis of expected costs.

Since most roads are built for local or national governments with large financial resources relative to the costs of a particular project, it may be argued that least expected costs are a valid criterion for pavement design decisions.

This paper illustrates the use of the decision tree approach in connection with pavement design, but it is equally applicable to a host of other engineering decisions.

Whatever the final decision, this approach to the pavement design situation provides a useful guide to the engineer and decision maker alike.

5. CONCLUSIONS

There are many areas of uncertainty in decisions relating to the design of road pavements for an agreed economic life. It is believed that the process of placing subjective probabilities on the possible outcomes resulting from the use of different designs provides a numerical framework which enables engineering judgements to be taken into account in making the final decision. The main steps in analysing such a decision are:

a) Describe the possible outcomes of each design proposal in the form of a decision tree
b) Place a cost value on each possible outcome
c) Assign subjective probabilities to the occurrence of each possible outcome. (The sum of probabilities of all the outcomes of any one decision must be 1.0).
d) Calculate the expected discounted cost of each design proposal.

It is not suggested that decisions should be made automatically on the basis of 'least expected cost'. However, it is recommended that this information should be available, so that it can be considered along with political and financial criteria by the decision maker.

In this paper, the aim has been to give a simple introduction to the possible use of decision analysis in pavement design problems, and hopefully in other highway engineering problems too.

6. ACKNOWLEDGEMENTS

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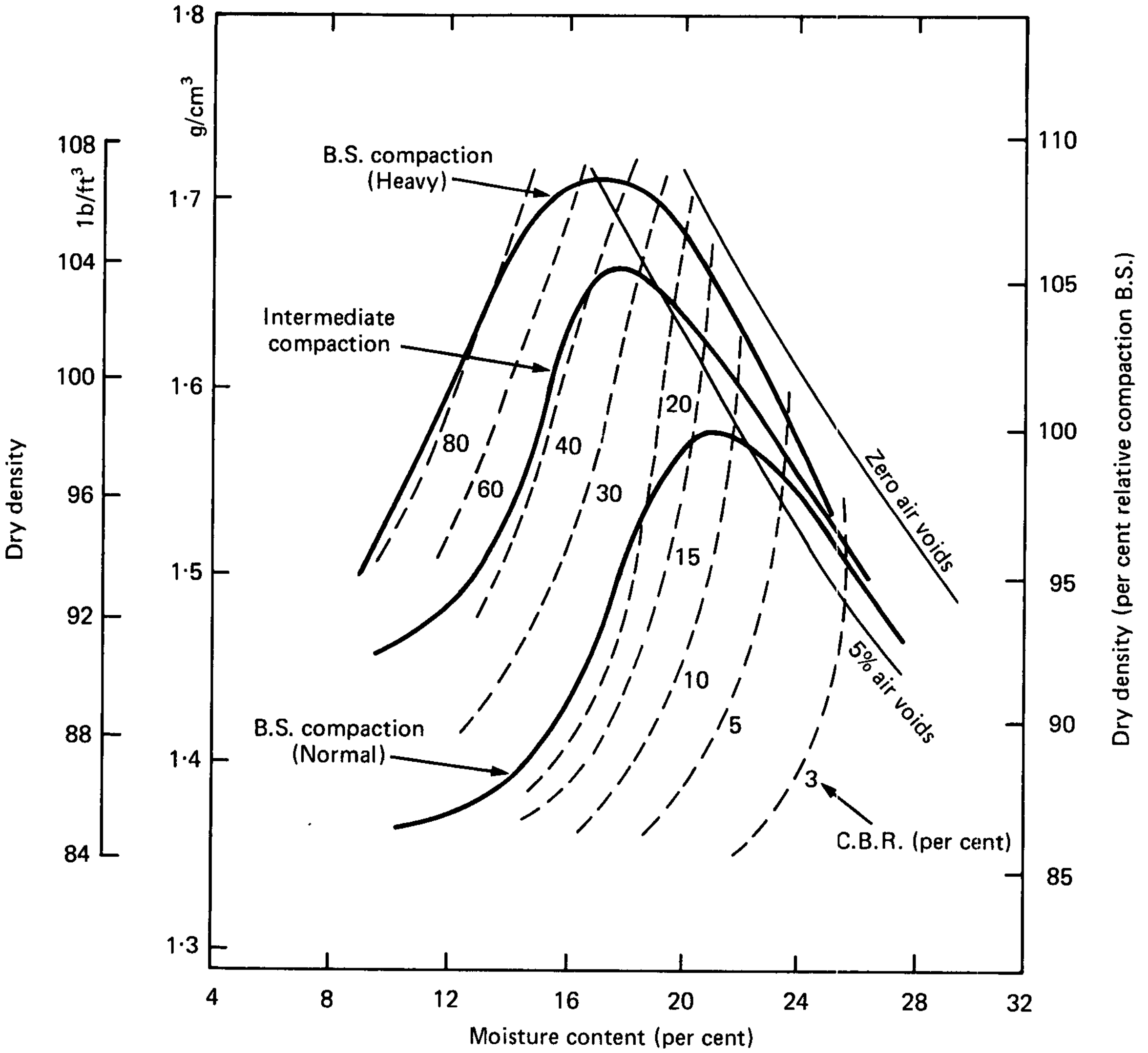
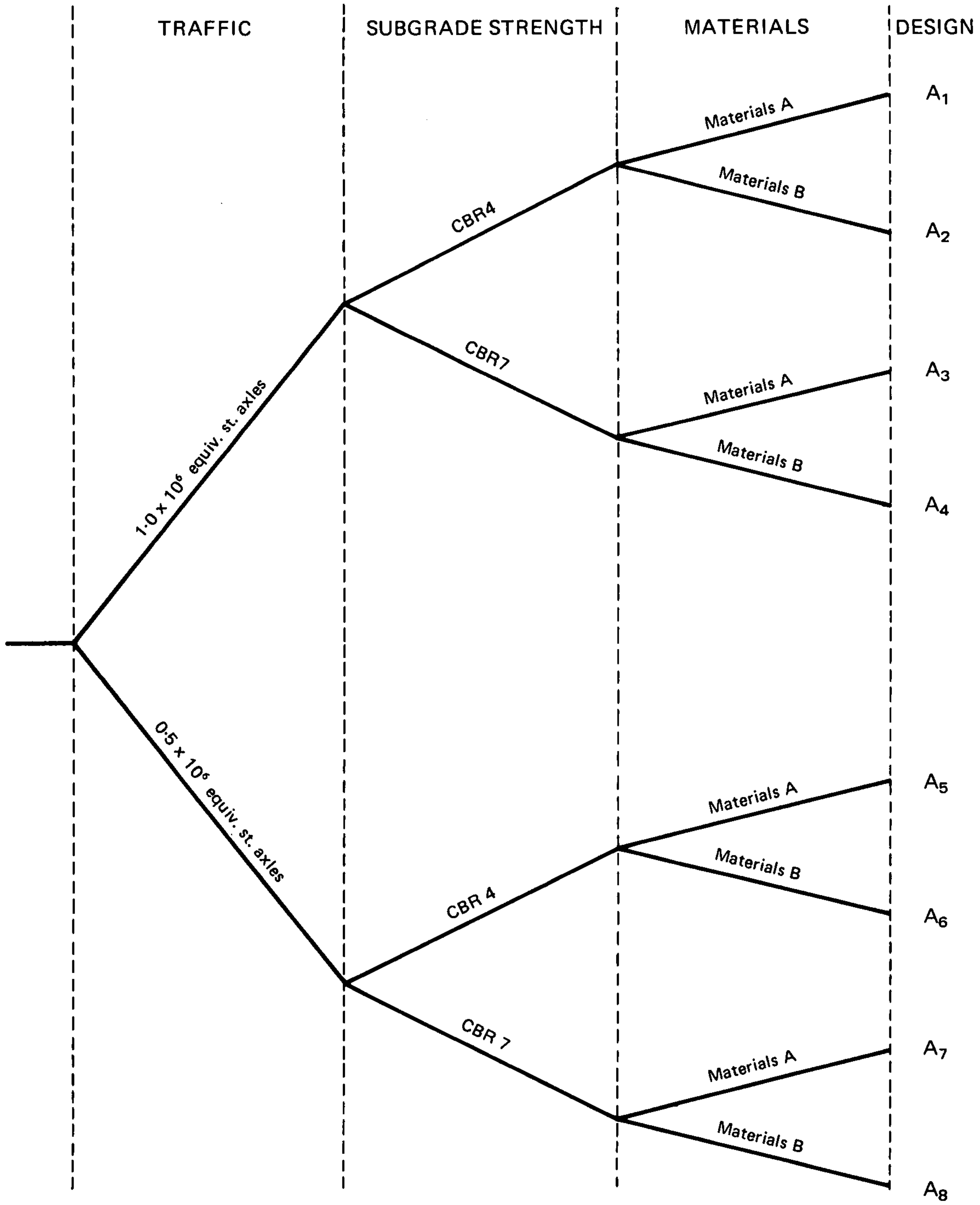


Fig. 1 DRY DENSITY–MOISTURE CONTENT–C.B.R. RELATIONSHIPS FOR A SANDY-CLAY SOIL



Note:- In this particular figure no interdependence of actions should be inferred from the 'tree' structure of the diagram. Design decisions relating to traffic, subgrade strength and materials may be taken independently.

Fig. 2 EXAMPLE OF POSSIBLE COURSES OF ACTION IN THE PAVEMENT DESIGN PROCESS

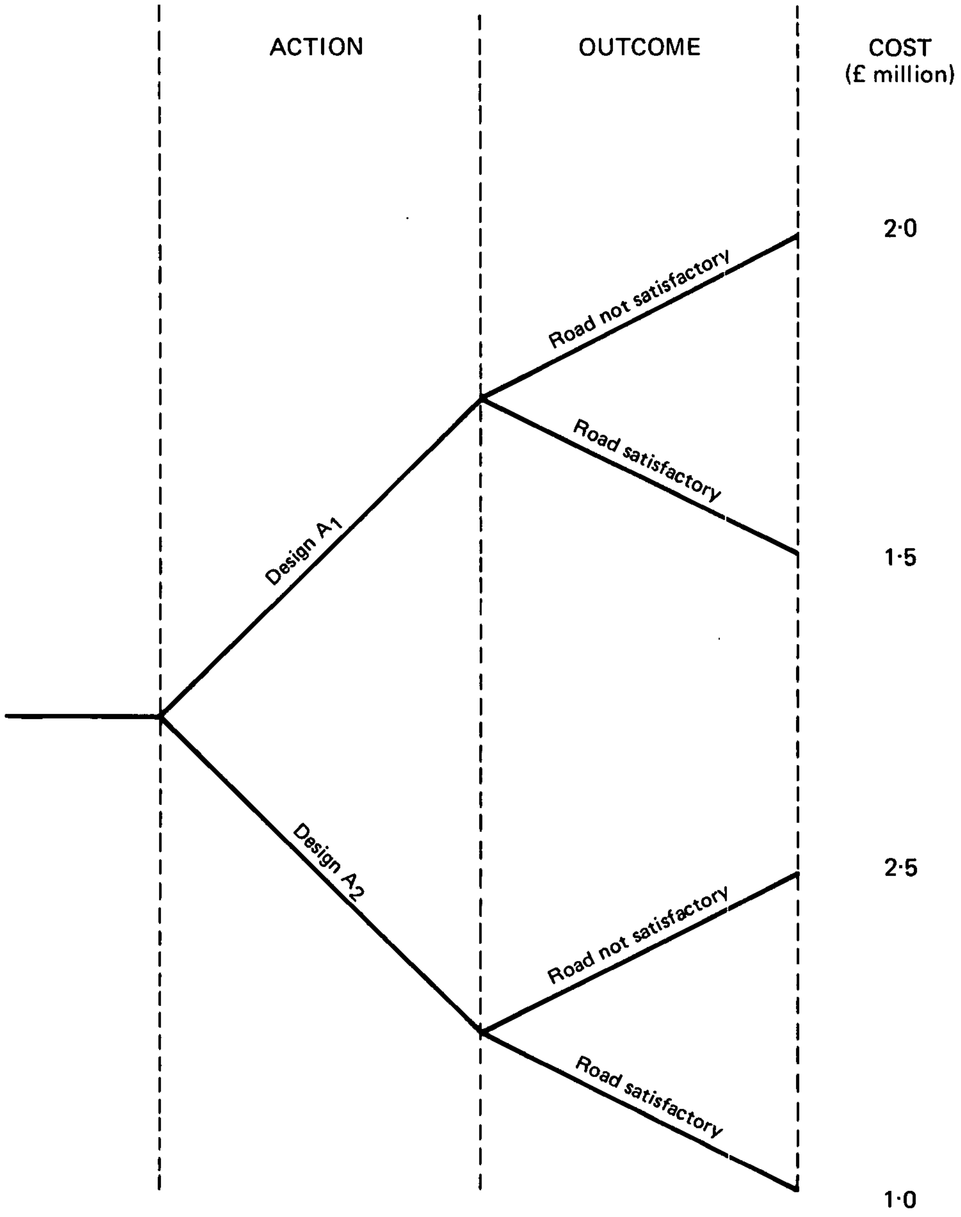


Fig. 3 DECISION TREE — BASIC PROBLEM

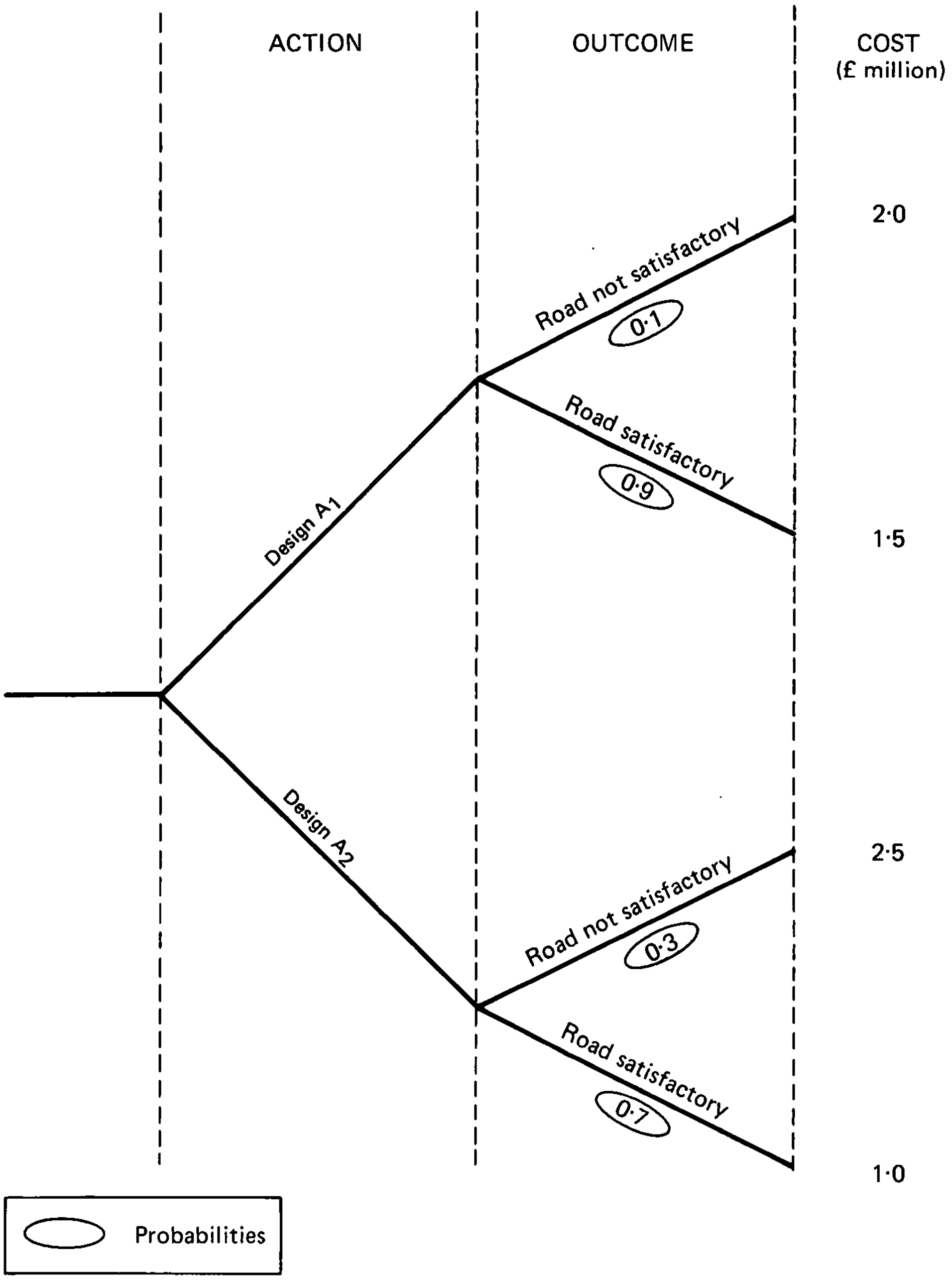


Fig. 4 BASIC PROBLEM WITH PROBABILITIES

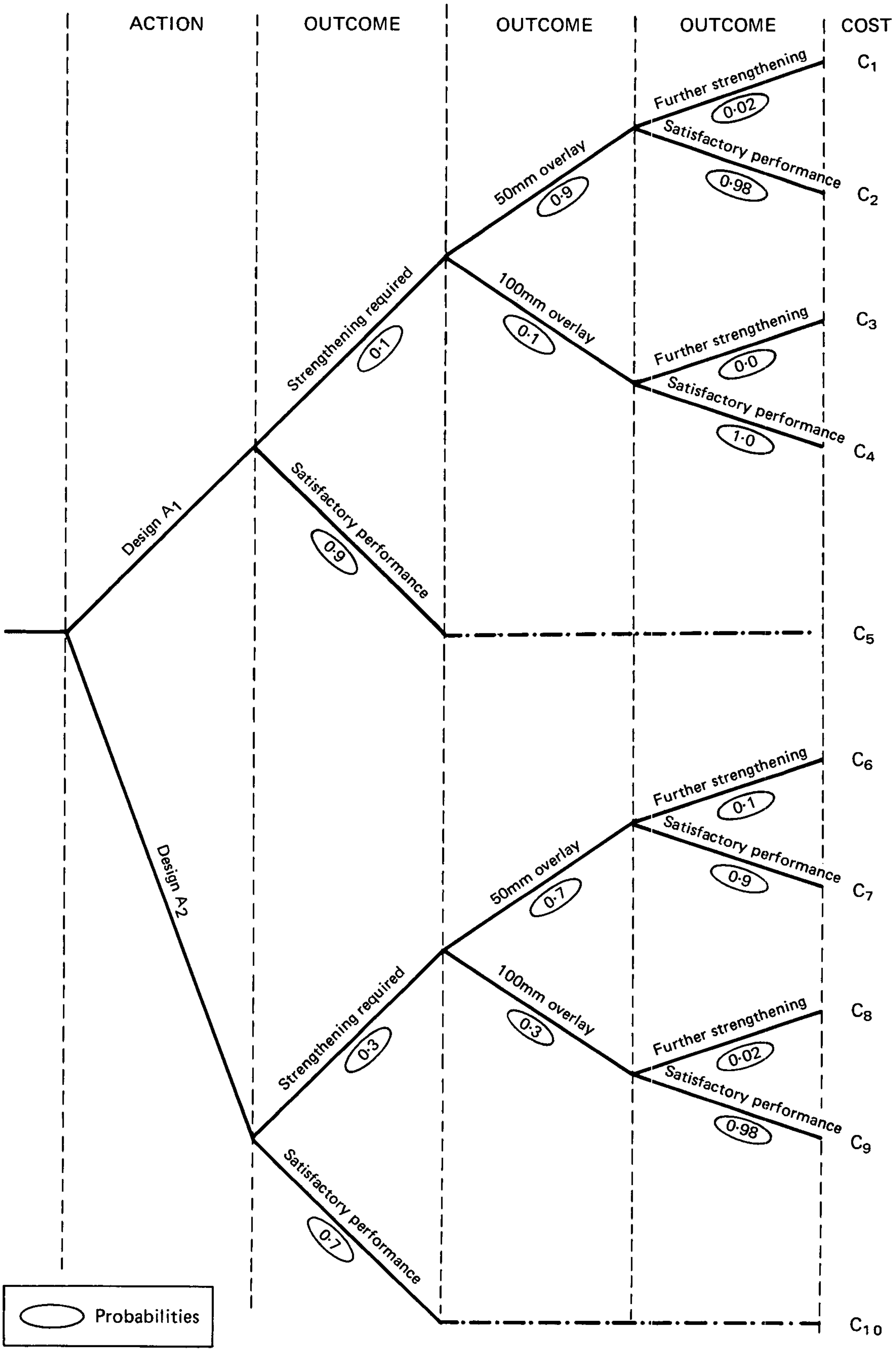


Fig. 5 DECISION TREE FOR PAVEMENT DESIGN

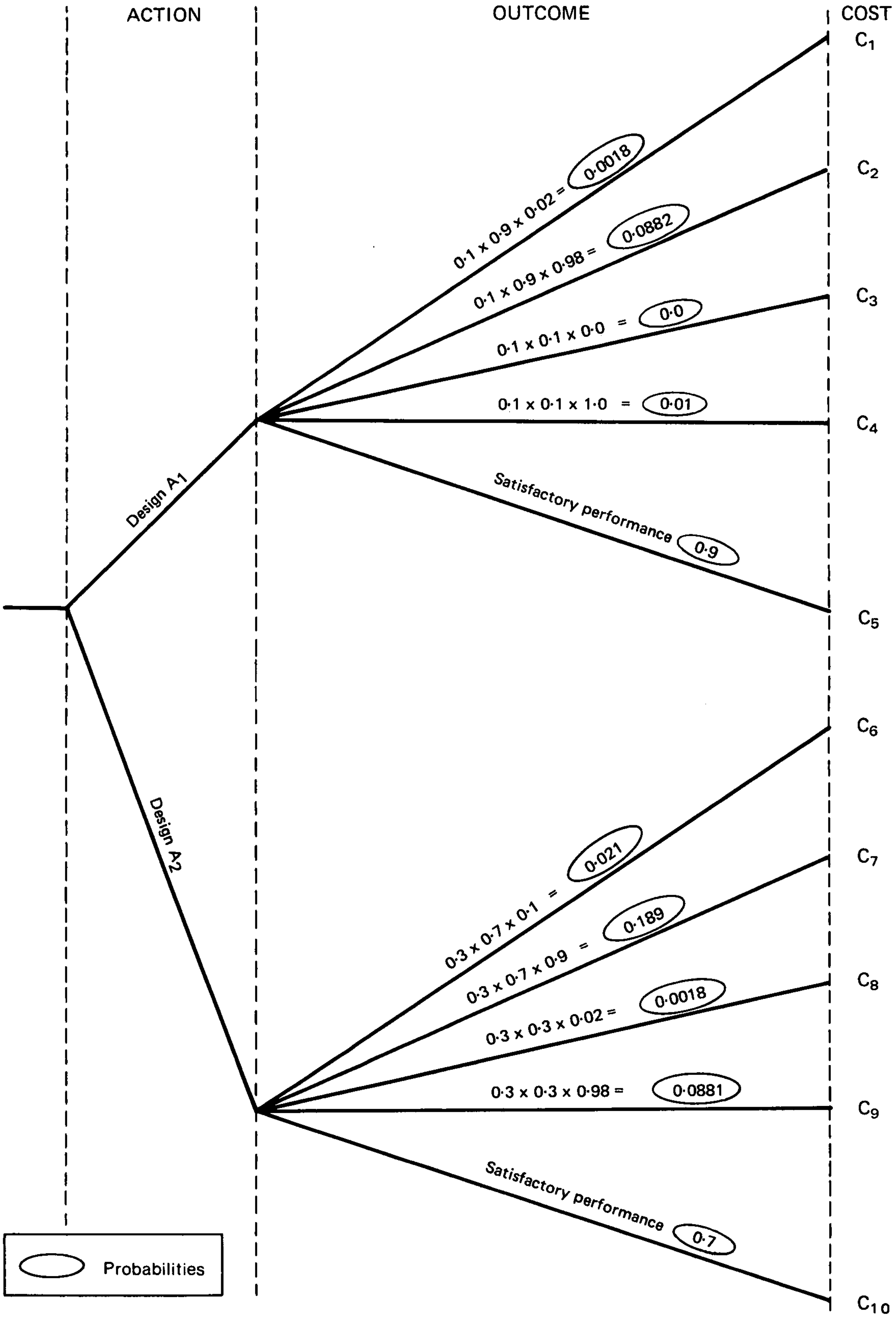


Fig. 6 ALTERNATIVE TO FIG. 5

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