

TRRL Supplementary Report 537

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Pavement engineering in developing countries

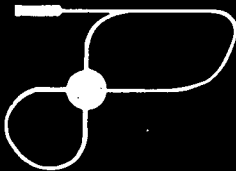
by

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TRANSPORT and ROAD RESEARCH LABORATORY

Department of the Environment
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DIGEST OF REPORT



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Digest SR 537

PAVEMENT ENGINEERING IN DEVELOPING
COUNTRIES

Author C I Ellis

PAVEMENT ENGINEERING IN DEVELOPING COUNTRIES

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Since most developing countries lie in the tropics or sub-tropics the differences between pavement engineering in temperate industrialised countries and developing countries are often thought of almost exclusively in terms of climatic differences. Whilst these differences are substantial, a considerable body of knowledge exists that enables experienced designers to incorporate reasonably satisfactory provisions within their designs for all but the most extreme effects of tropical climates.

Equally important differences between pavement engineering in developing and industrialised countries are the greater variability of construction materials, quality of construction, and the larger fluctuations in the volume and weight of road traffic that are typically encountered in developing countries.

Because of the large variability of these factors the design of road pavements in developing countries must either include a higher 'factor of safety' than is usual in industrialised countries, or a higher risk of failure must be accepted. The latter course is the one most commonly adopted. It is an advantage in that it minimises the demands made by road-building on scarce capital resources and the disadvantages of partial or premature pavement failure are much reduced by the short 'design life' generally adopted and the relative ease with which repairs can be made on the typically uncongested roads.

In the few fortunate oil-rich developing countries the pavement engineering situation has, however, radically changed in recent years. Low risks of failure and long design lives are now often demanded in these countries; designers respond by adopting generous safety factors to compensate for the large uncertainties that remain in the prediction of traffic and the variability of materials and quality of construction.

An important aspect of pavement engineering in developing countries that has no parallel in most industrialised countries is the extent to which unsurfaced roads contribute to national road networks. Unsurfaced roads of all types play a vital role in the economic and social life of many of these countries, and such roads, carrying several hundred vehicles per day, are not uncommon.

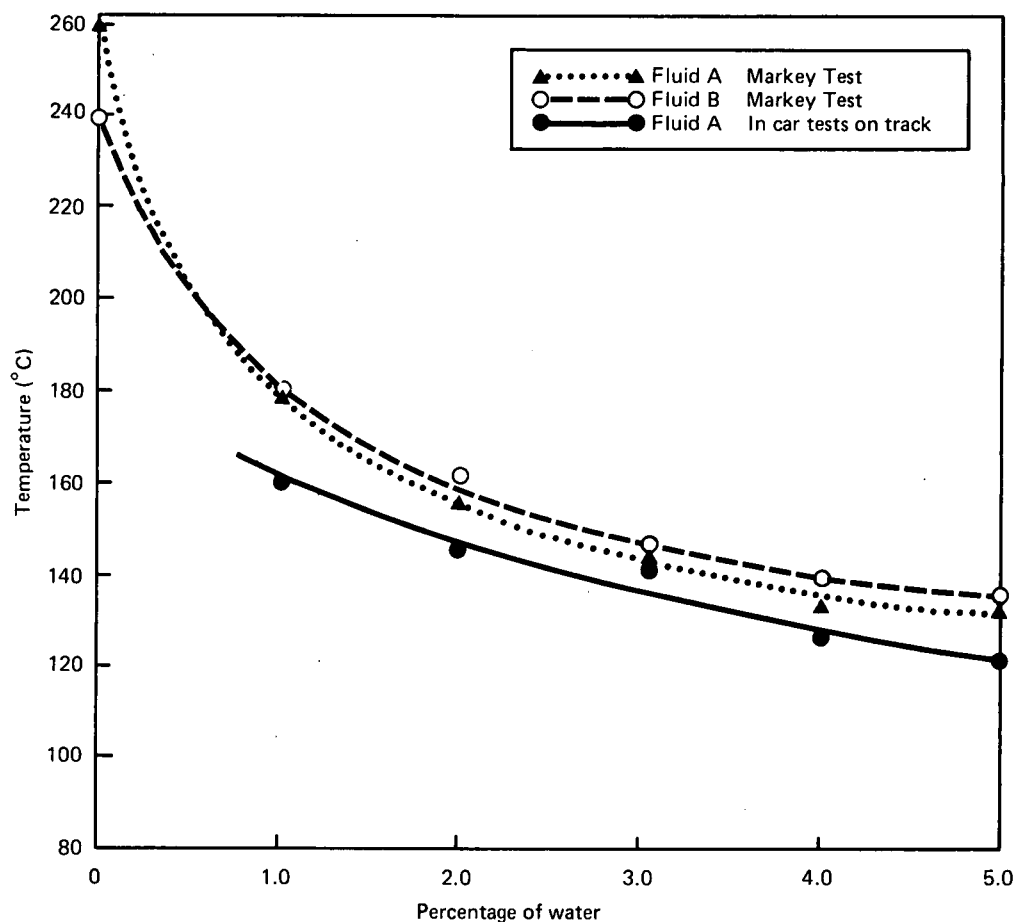
In this respect consideration is given to the traffic bearing ability of earth roads related to the important factors of route selection and drainage. The design of gravel roads is considered in terms of structural thickness and the selection of suitable gravels.

The wide range of pavement design methods for bitumen surfaced roads are described and discussed by reference to the pavement thicknesses recommended by such methods. Such comparisons are expressed in terms of 'Tropical Structural Number' (TSN) which is a modified form of the AASHTO Structural Number.

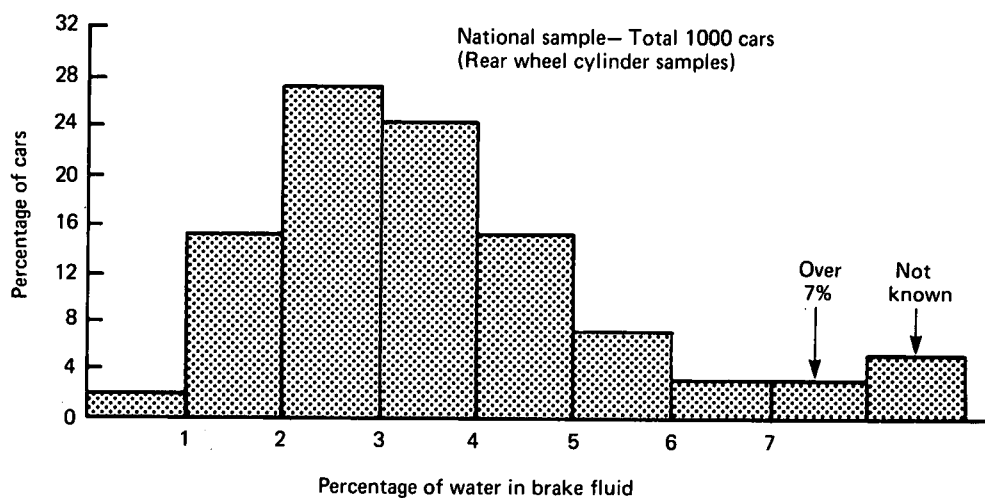
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Digest Fig. 1 VAPOUR LOCK TEMPERATURES OF BRAKE FLUID AT DIFFERENT WATER CONTENTS



Digest Fig. 2 WATER CONTENT IN THE BRAKE FLUID OF A NATIONAL SAMPLE OF CARS

The work described in this Digest was carried out in the Vehicle Safety Division of the Safety Department of TRRL.

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**TRANSPORT and ROAD
RESEARCH LABORATORY**

Department of the Environment
Department of Transport

SUPPLEMENTARY REPORT 537

PAVEMENT ENGINEERING IN DEVELOPING COUNTRIES

by

C I Ellis

The work described in this Report forms part of the programme carried out for the Overseas Development Administration but any views expressed are not necessarily those of the Administration

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PAVEMENT ENGINEERING IN DEVELOPING COUNTRIES

ABSTRACT

This Report discusses the reasons for the differences between pavement engineering in temperate climates and in developing countries with tropical or sub-tropical climates.

The importance of earth and gravel roads in developing countries is emphasised, and commonly used methods of pavement design for bitumen surfaced roads are described and compared. Recent developments in techniques and equipment for improving construction standards and for assessing road performance are described.

The use of appropriate forms of contract is briefly discussed and the need to improve knowledge of the factors which would enable total transport costs to be minimised is emphasised.

1. INTRODUCTION

Since most developing countries lie in the tropics or sub-tropics the differences between pavement engineering in temperate industrialised countries and developing countries are often thought of almost exclusively in terms of climatic differences. Whilst these differences are substantial, a considerable body of knowledge exists that enables experienced designers to incorporate reasonably satisfactory provisions within their designs for all but the most extreme effects of tropical climates.

Equally important differences between pavement engineering in developing countries and industrialised countries are the greater variability of construction materials, quality of construction, and the larger fluctuations in the volume and weight of road traffic that are typically encountered in developing countries.

Because of the large variability of these factors the design of road pavements in developing countries must either include a higher 'factor of safety' than is usual in industrialised countries, or a higher risk of failure must be accepted. The latter course is the one most commonly adopted. It is an advantage in that it minimises the demands made by road-building on scarce capital resources, and the disadvantages of partial or premature pavement failure are much reduced by the short 'design life' generally adopted and the relative ease with which repairs can be made on the typically uncongested roads.

In the few fortunate oil-rich developing countries the pavement engineering situation has, however, radically changed in recent years. Low risks of failure and long design lives are now often demanded in these countries; designers respond by adopting generous factors of safety to compensate for the large uncertainties that remain in the prediction of traffic and the variability of materials and quality of construction.

An important aspect of pavement engineering in developing countries that has no parallel in most industrialised countries is the extent to which unsurfaced roads contribute to national road networks. In developing countries unsurfaced roads carrying several hundred vehicles per day are not uncommon, and unsurfaced roads of all types play a vital role in the economic and social life of many of these countries. The techniques of constructing and maintaining unsurfaced roads are thus an important part of pavement engineering in developing countries.

The selected statistics shown in Table 1 illustrate the differences between roads and road transport in developing countries and in industrialised countries.

TABLE 1
Selected statistics of roads and road transport in developing and industrialised countries

Country	Gross national product per capita US \$ (ref. 1)	Length of bitumenised or concrete road km x 10 ³ (ref. 2)	Length of earth or gravel road km x 10 ³ (ref. 2)	Density of road networks km per km ² (ref. 3)	Numbers of commercial vehicles* per km of road
United States	6 670	2 925	3 215	0.66	4.29
France	5 440	707	87	1.4	2.78
United Kingdom	3 590	331	12	1.49	5.36
Brazil	920	77	1 235	0.15	0.76
Sierra Leone	190	1	6	0.10	0.64
India	140	409	486	0.27	0.46
Ethiopia	100	3	6	0.007	1.19

* Trucks and buses.

2. HIGHWAY PAVEMENT ENGINEERING

Highway pavement engineering may be defined as the process of designing, constructing, and maintaining highway pavements in order to provide a desired 'level of service' for traffic. In the pavement design part of this process, designers make assumptions about the methods of construction that will be employed and the level of maintenance that the pavement will receive throughout its design life. Clearly both the initial standard of construction and the level of maintenance affect the level of service provided by the pavement, these two factors being very closely inter-related. In the USA Hudson⁴ has drawn attention to the interdependence of these factors and the fact that the design and construction of a road pavement is not a single-phase process, but is merely the beginning of a continuing process in which maintenance, traffic, climate and the required level of service are all contributory factors. In Britain the costs of constructing and maintaining road pavements over a 50 year design life have been analysed⁵.

In the case of low-cost roads, typical of most developing countries, the influence of maintenance on the level of service provided by the pavement will generally be much stronger than is the case with heavier duty pavements. For unsurfaced roads the level of maintenance is at least as important as the initial construction standard in determining the level of service provided.

Ideally at the design stage, the designer, in consultation with the authority that will maintain the road, should select the combination of initial construction standard and subsequent maintenance that will provide the level of service required over the design life of the road in the most cost-effective way. In practice, in developing countries the designer rarely has sufficient information to make a quantified assessment of the appropriate balance between the initial construction standard and the level of maintenance, and because of uncertainty about the provision of maintenance when it is needed, he will often tend to enhance the standard of initial construction so as to minimise

future maintenance requirements. Some advances are being made however in providing designers with quantitative information on the 'trade-off' between the standards of construction and maintenance of roads typical of those found in developing countries. In recent years models have been produced that allow designers not only to quantify the interaction between construction and maintenance standards, but also to calculate their combined effect on vehicle operating costs, and hence to produce a design and specify a maintenance strategy that will minimise the sum of construction, maintenance, and vehicle operating costs over the design life of the pavement. The sum of these three costs has been called the 'total transportation cost', and whilst these costs do not by any means represent all the costs involved in road transport, they are by far the most significant costs on non-urban roads in developing countries.

2.1 *Cost models*

The initiative for developing cost models for roads in developing countries was taken in the early 1970s by the World Bank. The World Bank recognised the need to improve knowledge of the interaction between road construction costs, road maintenance costs, and vehicle operating costs, in order to improve the quality of investment decisions in the roads sector in developing countries. As a first step a computer model was built on the basis of existing knowledge⁶. Subsequently a major study was undertaken in East Africa by the Overseas Unit of TRRL^{7,8} in collaboration with the World Bank to improve knowledge of the effects of road conditions on vehicle operating costs and the rates of deterioration of road pavements. As a result of these field studies empirical relationships were derived that have been incorporated into a computer model (RTIM)⁹. This model calculates the sum of road construction costs, road maintenance costs, and vehicle operating costs over the 'design life' of the road for a non-urban road project in a developing country.

Further improvements to these empirical relationships will be forthcoming from World Bank sponsored studies which are in progress in Brazil¹⁰ and India, and from TRRL studies in the Caribbean. In addition to these field studies, model development is being undertaken by the Massachusetts Institute of Technology with the objective of producing a model capable of evaluating 'total transport costs' for road networks rather than just for single road links.

3. EARTH AND GRAVEL ROADS

Not surprisingly the engineering of earth and gravel roads has received much less attention from highway engineers and research workers than the engineering of surfaced roads. Most of the technical literature on unsurfaced roads is concerned with the techniques and the organisation of maintenance, and the selection and specification of natural materials for constructing gravel roads. Several methods have been published for designing the thickness of unsurfaced roads on a structural design basis, and three of these methods are described below. However, the relevance of the concept of structural design to unsurfaced roads is not widely accepted.

In recent years there has been a growing awareness of the need to improve knowledge of the relationships between the construction and maintenance standards, the climate, the traffic, and vehicle operating costs on unsurfaced roads. The need arises because of the desire of transport planners to improve the quality of investment decisions in the rural road sector in developing countries. A considerable amount of unrecorded local knowledge about the interaction between many of these factors exists in developing countries, but quantified data is very scarce.

3.1 *Earth roads*

The distinction between earth and gravel roads is rarely well-defined, but a commonly accepted distinction is that earth roads are constructed only of the natural materials that are encountered on the road line or immediately adjacent to it. Gravel roads on the other hand may incorporate imported material, normally a selected natural gravelly material, but sometimes processed gravels may be used.

The best service will be obtained from earth roads if they are located on the better drained parts of the terrain, and on the more granular soils if any choice of soil type is available. In most situations skill in locating earth roads in the landscape is thus fundamental to their subsequent performance. Often the location of earth roads is undertaken on the basis of a brief reconnaissance of the ground by an engineer, but in complex terrain much better results will be obtained by using terrain evaluation techniques^{11,12,13} assisted by aerial photography and other remotely sensed ground data.

Clearly the traffic-bearing ability of earth roads depends heavily on the type of soil forming the running surface, and on the prevailing moisture conditions. The ability of earth roads to carry traffic can be substantially enhanced if they are 'engineered' by such measures as raising the formation in low-lying areas, clearing trees and shrubs well back from the road so that the sun and wind can more readily dry out the road surface when it is wet, cambering the surface, and cutting suitable side-drains. The principles of good construction and maintenance practice for earth roads are illustrated in Figure 1. In favourable circumstances earth roads can carry substantial volumes of traffic, as is evidenced for example by the behaviour of 'sabkha' roads¹⁴ in certain arid areas, and the roads built on the 'red-coffee' soils in Kenya.

A comprehensive guide to the construction and maintenance of earth roads has been written by Mellier¹⁵. More recently some interesting research on the trafficability of soils has been undertaken at Vicksburg¹⁶, the results of which are illustrated by the nomograph shown in Figure 2. This nomograph indicates the number of repetitions of wheel loads of different magnitudes that can be carried by soils of different strengths. The definition of the terminal condition in this work was when the rut-depth in the soil exceeded 75 mm. If the strength of an earth road is known (in terms of its California Bearing Ratio (CBR) value), the nomograph permits predictions to be made of the load carrying ability of the road.

3.2 *Gravel roads*

There are two basic attitudes to the design of the thickness of gravel roads. One of these is the quantitative structural design approach, examples of which are the methods suggested by Mellier¹⁵ and Hammitt¹⁷. This approach presents the designer with the difficult problem of deciding what moisture content should be assumed for the subgrade soil and the gravel layer, since clearly in seasonal climates there will be a large change in moisture content and hence the strength of these materials between the wet and dry seasons.

The other approach to the design of gravel roads is that described by O'Reilly and Millard¹⁸ in which the assumption is made that thickness design of gravel roads is unnecessary, and the important issue is the selection of gravel material with specified grading and plasticity characteristics which is placed in a layer of standard thickness (150 to 200 mm). This approach is the one usually adopted in developing countries in the tropics in which

subgrades under adequately maintained gravel roads are commonly strong enough for the greater part of the year to support the imposed wheel loads with no more than 150 mm of gravel cover. Table 2 gives values for the plasticity characteristics of gravel surfacing materials typically specified in different climatic zones. In either case provision has to be made for the replacement of gravel that is lost over a period of time due to the action of traffic and weather.

TABLE 2
Plasticity characteristics preferred for gravel surfacings¹⁸

Climate	Liquid limit not to exceed (%)	Plasticity index range (%)	Linear shrinkage range (%)
Moist temperate and wet tropical	35	4–9	2.5–5
Seasonally wet tropical	45	6–20	4–10
Arid or semi-arid	55	15–30	8–15

In practice the choice of gravel material is limited by what is available, and economy in design depends on the skill and resources that can be deployed to locate the very best materials that exist within an economic haul distance from the road. The terrain evaluation approach^{11,12,13} can be of great assistance in the location of gravel materials within the landscape.

In areas with strongly seasonal climates, it may not be economically feasible to build gravel roads on plastic subgrades that are capable of sustaining traffic throughout the wet season without excessive deformation. In these circumstances the level of service provided can usually be maintained at an acceptable level by increasing the frequency of grading, or in some areas where this is not possible, roads are closed for short periods after heavy and prolonged rain to prevent traffic causing excessive deformation when the subgrade is saturated.

Maintenance has a very strong influence on the performance of gravel roads. At traffic flows of more than 30 or so vehicles per day most gravel roads require grading at regular intervals of time to remove corrugations, to restore the transverse profile, and to bring back into the centre of the road gravel that has been thrown to the sides by the action of traffic¹⁹. In addition, the clearing of side ditches and the restoration of material removed by erosion are required at regular intervals. All these operations are necessary if the level of service provided by a gravel road is to be maintained, but perhaps the crucial operation is the maintenance of an adequate camber. Camber must be sufficient to prevent rainwater being retained on the surface of the road. If it is not, the road will deteriorate very rapidly in wet weather.

3.3 *Recent developments*

The techniques of designing and constructing earth and gravel roads have not changed significantly for many years. There are, however, two recent developments that are of some interest. One of these is the growing interest among highway planners and engineers in quantifying, for a particular climatic zone, the relationships between traffic volume, construction standards, rate of deterioration, and maintenance. Knowledge of these relationships is

required if cost-effect decisions are to be made about the construction of unsurfaced roads, or economic maintenance strategies are to be devised. In a number of developing countries empirical relationships have been devised in the past that link the frequency of grading necessary to maintain an acceptable level of service to the volume of traffic, and also in some cases to the type of gravel surfacing. Only recently, however, have quantified relationships of this kind been based on systematic measurements of road surface conditions, or included quantification of the effect of surface condition on vehicle operating costs. For example, in the study in East Africa^{7,8} relationships linking the following variables were established for several types of gravel road:

- (a) the volume of traffic;
- (b) the longitudinal roughness of the road surface;
- (c) the depth of ruts formed by the traffic;
- (d) the amount of gravel 'lost' from the road surface due to the action of traffic and erosion;
- (e) the longitudinal gradient of the road;
- (f) the rainfall.

Further studies are in progress that will improve these relationships and will extend them to other materials and climatic zones.

A second recent development in the field of earth and gravel road construction is the widespread renewed interest in employing labour-intensive methods of construction in developing countries. In several Asian countries labour-intensive methods have traditionally been employed on a large scale for civil construction projects. In many other developing countries, however, the construction of roads by labour-intensive methods has not hitherto been undertaken except on a small-scale and piecemeal basis. Recent studies sponsored by the World Bank²⁰ and the International Labour Organisation²¹ have shown that labour-intensive methods can in general produce the same quality of construction as equipment-intensive methods, and that they are economically justifiable in countries where the shadow daily wage* for labour is less than about US \$ 1.50 to \$ 2.00. This is the situation in more than forty countries, in several of which national programmes for labour-intensive road construction have recently been started or are planned.

4. BITUMEN SURFACED ROADS

4.1 *Current design methods*

Very few of the various methods of pavement design that are in general use throughout the world have been devised specifically for the design of pavements in tropical developing countries. Two exceptions are TRRL Road Note 31²², and the French CEBTP design manual for tropical countries²³. Other popular methods of pavement design, such as the AASHTO method²⁴ and its derivatives, though derived empirically in industrialised countries with temperate climates, are nevertheless often used for the design of pavements in the tropics.

* In many developing countries the wages paid often do not reflect the true value of labour to the economy. It is this latter which is relevant when comparing labour and capital intensive methods and it is termed the 'shadow wage'. For further amplification see Ministry of Overseas Development – Guide to the Economic Appraisal of Projects in Developing Countries. London, 1972 (H M Stationery Office).

Comments on the appropriateness of these methods for designing pavements in tropical developing countries are made below.

4.1.1 TRRL Road Note 31: This pavement design guide gives recommendations for the design of bitumen-surfaced roads carrying up to 2.5 million equivalent standard axles per lane in tropical and sub-tropical countries. The guide offers the designer the choice of two simple standard pavements, and provides for the thickness of the sub-base to be varied to suit the strength of the subgrade.

Particular attention is given in the guide to two aspects of pavement design that are of special importance in most developing countries:

- (1) detailed consideration is given to the influence of tropical climates on moisture conditions in road subgrades;
- (2) attention is drawn to the advantages of adopting a stage construction approach to road building in situations where traffic growth rates are high or long-term predictions are uncertain.

The guide expresses the strength of the subgrade soil in terms of its CBR measured at a moisture content equal to the wettest moisture condition likely to occur in the subgrade after the road has been constructed.

Traffic loading is expressed in terms of equivalent standard axles, on the same basis as that used in the AASHTO method.

The expression used by the Overseas Unit, TRRL, for defining the equivalence factor of any axle-load traversing typical roads in developing countries is given by:

$$N = \left(\frac{L}{L_s} \right)^{4.55}$$

ie one application of the axle-load L causes the same amount of structural damage as N applications of the standard axle-load L_s (8160 kg).

The guide, which has been derived empirically, suffers the disadvantages that all such methods share, namely that it cannot be applied with confidence to design situations that lie outside the range of conditions within which it has been derived. Nevertheless it does offer the designer a wide choice of pavement material options and is suitable for the design of medium and lightly trafficked roads in any tropical or sub-tropical environment.

4.1.2 CEBTP pavement design manual for tropical countries: This manual is widely used in French-speaking developing countries in the tropics. Traffic is categorised into four classes and a catalogue of four basic pavements is recommended to match these. Subgrade strength is expressed in terms of CBR, and the thickness of the base and sub-base of each class of pavement can be varied within limits to take account of differences in subgrade strength.

The categorisation of the traffic loading can be made in two ways:

- (1) on the basis of the average volume of traffic per day (all vehicles) assuming a design life of 15 years and 30 per cent 'heavy' vehicles in the traffic stream;

(2) on the basis of the cumulative number of 'heavy' vehicles passing over the pavement during its design life.

A heavy vehicle is defined as one that has a total weight of more than 3 tonnes.

The guide also suggests that if more than 10 per cent of axle loads are greater than 13 tonnes extra pavement thickness may be required.

The manual, which is very simple to use, is essentially a modification of the original CBR method of design. It does not attempt to differentiate between axle loads of different magnitudes, and hence it cannot take account of the big differences in damaging power that can exist between similar volumes of traffic in different countries, or even on different roads within the one country.

4.1.3 AASHTO interim guide: This guide, which is based on empirical relationships derived from the AASHTO Road Test²⁵, was produced primarily for the design of pavements in the USA. Nevertheless it is sometimes used, not always very appropriately, for the design of pavements in developing countries in the tropics.

In the guide the predicted distribution of the axle loads that will traverse the pavement throughout its design life is expressed in terms of the equivalent number of 8.2 tonne 'standard' axles. This is achieved by the application of 'equivalence' factors (see reference 56). These factors relate the damage done to the pavement by an axle load of any magnitude to the damage done by a standard 8.2 tonne axle load. The factors follow approximately a 'fourth power law'; that is, if an axle load is doubled, the damage it will inflict on the pavement will be sixteen times greater. This concept of axle load equivalence factors is now widely accepted, and is incorporated into several other methods of pavement design. However, there is a great deal of uncertainty about the magnitude of the power in the 'power law', and the extent to which it is influenced by overall pavement strength and the types of materials used in the pavement.

The AASHTO guide defines subgrade strength in terms of a 'soil support value', ranging from one for very weak subgrades, to ten for subgrades as strong as crushed rock base material. Pavement thickness is expressed in terms of a Structural Number (SN), ranging from 1.0 to 6.0, which is an index of the strength of pavement required. This is then modified by the application of a Regional Factor which adjusts the design to suit local climatic conditions. Finally, layer thicknesses are determined, the contribution of the layers of the selected pavement materials to the pavement strength is estimated by applying coefficients (sometimes called 'layer equivalencies') that have been assigned to the commoner materials on the basis of the results of the AASHTO test and subsequent experience.

The problem facing a designer applying the AASHTO guide to the design of a pavement in a typical developing country situation is the difficulty in estimating the appropriate Regional Factor to use, and in determining the appropriate coefficients to apply to the pavement materials available. The same problem arises whenever an empirically derived design method is applied in conditions outside the range of experience on which it has been based.

The range of Regional Factors employed in the USA is large, and is rather arbitrarily applied. In dry frost-free regions the Regional Factor used can be as low as 0.5, whilst in regions where subgrades freeze in the winter but thaw out in the spring the Regional Factor used may be as high as 4.0 or 5.0. This range represents an increase

in thickness of 50 per cent for pavements with a SN of 2.5 or less, typical of most surfaced roads in developing countries.

In South Africa, where a modified form of the AASHTO design method is employed and the climate ranges from moist sub-tropical to arid, Regional Factors in the range 0.3 to 0.75 are recommended²⁶. In Mexico a Regional Factor of 0.2 is used in semi-arid situations.

As regards the appropriate coefficients to apply to different pavement materials, a considerable amount of information exists about the commoner pavement materials used in the USA, such as asphaltic concrete surfacing materials and crushed rock and gravel base materials. In developing countries in the tropics the indigenous pavement materials available will often not have any close parallel in North America and designers using the AASHTO method will have to rely on judgement in assigning coefficients to the materials selected.

4.1.4 Shell modified design charts: The shell design charts were first published in 1963²⁷, but have been modified subsequently to take account of the effects of high road temperatures on the moduli of bituminous materials²⁸. They are therefore now better suited to the design of road pavements in developing countries in the tropics. The charts were derived from consideration of the basic properties of bituminous mixes as determined by mechanical tests in the laboratory, and the allowable strains in the subgrade and asphalt surfacing layer. The analytical approach to pavement design, which is the basis of both the original Shell design charts and the more recent more comprehensive method²⁸, is fully described in reference 56.

The original charts are held to have been well-supported by the evidence of the performance of roads, but the recently modified charts have yet to be similarly validated.

In using the modified Shell charts it is necessary to estimate the weighted mean annual air temperature (MAAT) of the location in question. This can be obtained from mean monthly air temperatures by use of a given weighting curve. Simple meteorological information of this kind can usually be obtained in most countries, or can be estimated with adequate accuracy.

4.1.5 Other methods: Various other methods of pavement design are used from time to time in developing countries. The most significant of these are RRL Road Note 29²⁹, the Asphalt Institute method³⁰, and the Canadian Good Roads Association method³¹. None of these methods is well suited to the design of roads carrying less than about 500 vehicles a day, which form the majority of the surfaced roads in most developing countries. Moreover, whilst these methods of pavement design can be used to design heavily-trafficked roads in developing countries, they do not have the facility for adjusting designs to take account of different climatic environments.

4.2 *Comparison of pavement design methods*

Valid comparisons between the different methods of pavement design described above are difficult to make. If common factors of safety and criteria for pavement failure were shared by all the methods, a comparison on the basis of the recommended thicknesses of similar materials would be a measure of the relative 'efficiency' or design economy of the different methods.

In fact, the failure criteria and factors of safety inherent in the various methods are all different, and in several methods they are not even clearly defined. Nevertheless some measure of the relative efficiency of the different design methods can be gained by comparing the pavement thicknesses recommended by the various methods for similar levels of traffic loading and subgrade strength.

In order to make these comparisons it is helpful to express pavement thicknesses in terms of a 'structural number', similar in concept to the SN used in the AASHTO design method. In the AASHTO method SN is given by:

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3$$

where a_1 , a_2 , and a_3 are layer coefficients, and D_1 , D_2 , and D_3 are layer thicknesses in inches. It should be recognised that assigning coefficients to particular materials can only be a very rough guide to the relative contribution different materials can make to the structural strength of a pavement. It is well known that the effective coefficient of a pavement layer is not only a function of the type of material but is also dependent on the thickness of the layer, the position of the layer in the pavement, the moduli and thicknesses of the other layers, the subgrade characteristics, and other factors. There are thus many reservations about the concept of layer coefficients, but nevertheless it will suffice for the purpose of making a rough comparison between current methods of pavement design.

Because the service temperatures of bituminous surfacings in most developing countries in the tropics are much higher than those experienced in the AASHO Road Test, it is necessary to assume different layer coefficients for bituminous layers from those given in the AASHTO guide if even rough comparisons between different design methods are to be made in the context of tropical environments. The AASHTO guide suggests a coefficient of between 0.44 and 0.40 for asphaltic concrete surfacings, but in a typical developing country situation it is assumed for the purposes of this comparison that 0.20 would be more appropriate. This assumption is made on the basis of the temperature/stiffness relationship for bituminous mixtures implicit in the modified Shell design charts²⁸, from which can be deduced the relations shown in Figure 3 between MAAT and layer coefficient. From Figure 3 it can be seen that in tropical climates the effective layer coefficient for asphalt surfacings ranged from about 0.10 for CBR 20 subgrades in the hottest climates, to about 0.37 for CBR 2.5 subgrades in sub-tropical climates.

Using values of 0.2 for a_1 , and the same values for a_2 and a_3 as are given in the AASHTO guide (eg granular base $a_2 = 0.14$, sub-base $a_3 = 0.11$), the modified structural numbers implied by the different design recommendations are compared in Figure 4. For convenience the modified structural number is plotted as 'Tropical Structural Number' (TSN), and Figure 4 shows how this is related to traffic loading on an average subgrade of CBR 8.

In calculating the TSN values that are plotted in Figure 4 it was assumed that the pavements had the minimum thickness of bituminous surfacing permitted by each design method. This minimises the influence on TSN of the value adopted for the coefficient a_1 , and is typical of developing country pavements which rarely have thick bituminous surfacings.

It is also assumed in Figure 4 that the subgrade strengths are assessed in the same way for each of the design methods. In fact each method suggests different ways of estimating the appropriate subgrade moisture content and

density at which to assess the subgrade strength. These variations increase even further the differences between the designs produced by the different methods shown in Figure 4.

Similarly, each design method suggests rather different ways of expressing traffic loading. Most methods convert the predicted axle load distributions into an equivalent number of standard axles, but there are considerable differences in the factors used for this.

Accepting these reservations about the basis of this comparison, it can nevertheless be concluded that there are very large differences between the designs produced by the various methods of pavement design, even when the same assumptions of subgrade strength and traffic loading are made. The TSN is in effect an index of pavement thickness, and it can be seen from Figure 4 that the more conservative design methods recommended pavements almost twice as thick as the least conservative. It can also be seen that the methods of pavement design issued specifically for use in tropical developing countries produce the most economical designs. This partly reflects the different standards of serviceability and failure criteria that are inherent in the different methods, but it also reflects different modes of failure and the absence of the damaging effect of frost in the tropics.

The comparisons made in Figure 4 demonstrate the degree of uncertainty that exists about the design of more heavily trafficked road pavements in the tropics, and points to the need for more research in this field.

4.3 Recent developments

4.3.1 Axle loads: In all countries increases in the volume of traffic and the size and weight of vehicles over the last two or three decades have necessitated the building of much stronger road pavements than those that sufficed earlier. In developing countries the rate of growth of traffic loading has been most dramatic. In part this is a reflection of the relatively small number of commercial vehicles that were in use in Third World countries twenty years ago, but it also reflects the absence of effective control of the weights and axle loads of vehicles in many countries. Indeed in some countries there is no restriction at all on axle loads.

As a result of the high rate of growth of traffic loading in developing countries, it is not uncommon for roads to fail prematurely because the traffic loading in service is several times greater than was assumed in the design. In recent years a considerable amount of information has become available about the axle loads on the roads in a number of developing countries^{32,33,34}. This has shown the strong influence that a relatively small number of vehicles with high axle loads can have on the rate of pavement damage of a typical main road in a developing country. For example, it is possible to envisage a situation in which the regular use of as few as one or two hundred vehicles with 20 tonne axle loads could severely damage a significant proportion of the paved road network of a developing country within a few months. This is because when overall volumes of traffic are low and axle loads are modest, the introduction into the traffic stream of a small proportion of vehicles with 20 tonne axle loads can double or treble the damaging power of the traffic. It is thus very important to control the upper limit of axle loads in developing countries.

This conclusion arises directly from the assumption that an axle load of 20 tonnes is roughly 300 times as damaging as one of 5 tonnes. This is the ratio given by axle load equivalence factors derived from the AASHO Road Test that are used in most methods of pavement design in current use. However, there are considerable

doubts about the validity of the AASHO Road Test equivalence factors for use in developing countries. They may under-estimate or over-estimate the damaging effect of heavy axle loads. The main reasons for these doubts are:

- (1) The maximum axle loads used in the AASHO Road Test were 13.6 tonnes for single axles, and 21.8 tonnes for tandem axle sets. In developing countries, single axle loads in excess of 20 tonnes are not uncommon, hence it is necessary to extrapolate well beyond the AASHO test results to derive equivalence factors for these loads.
- (2) There are considerable differences between the various interpretations that have been made of the AASHO Road Test results. Whilst Liddle's analysis³⁵ is most widely used, the analysis made by Shook and Finn³⁶ is also used to a considerable extent and these two interpretations give quite different results for the damaging effect of very heavy axle loads.
- (3) Frost was a critical factor in the deterioration of the AASHO Road Test pavements, but it is a negligible factor in most developing countries. In the interpretation of the results an attempt was made to separate the effects of frost on pavement deterioration from the traffic-induced effects, but this was not wholly successful.
- (4) The Road Test pavements were constructed on a weak subgrade, whereas most pavements in developing countries are built on strong subgrades.

Clearly there is a need to reduce the uncertainty that exists about the damaging power of heavy axle loads in typical developing country situations. Eventually the analytical pavement design approach will be developed to the point where consideration of empirically derived axle load equivalence factors will become irrelevant. However, this goal is still some way off, and in the shorter term research such as that being undertaken in South Africa using heavy vehicle simulators³⁷ offers the best chance of providing practical answers to these and other pavement design problems.

In recent years the world-wide growth in the movement of freight by road, and the production of a new generation of larger and more powerful commercial vehicles, has prompted governments in many countries to re-examine the maximum axle loads permitted on their national road networks. In general, the larger the vehicle and the heavier the axle load, the cheaper is the tonne-kilometre operating cost. In both developing countries³⁸ and industrialised countries³⁹ attempts have been made to deduce the optimum axle load at which the combined cost of vehicle operation, road construction, and road maintenance is minimised. Figure 5 indicates the nature of the relationships between axle load and the tonne-kilometre costs of vehicle operation and road construction and maintenance. There are of course big differences between the ideal 'optimum' axle load, the legal axle load limit, and the range of axle loads that are actually applied to a road system. The influence of the legal axle load limit on the actual distribution of axle loads naturally varies from country to country, depending on the degree of enforcement and other factors. Clearly this aspect must be carefully considered when making an analysis of the merits of a particular legal axle load limit. Similarly if an increase in legal axle load limit is being considered careful thought must be given to the effects on existing bridge structures and roads; it may well be that the costs of strengthening structures and adding expensive overlays to existing roads outweigh the benefits that would accrue from reduced tonne-kilometre operating costs.

Nevertheless, studies in some countries, notably Australia⁴⁰, have concluded that raising axle load limits would bring substantial national economic benefits. It is probable that similar conclusions could be reached in several developing countries, and that in the future legal axle load limits in the Third World will tend to rise, but that in parallel there will be stricter enforcement of these limits.

The Overseas Unit of TRRL has developed a portable weighbridge, and has gained experience with it in axle-load surveys in many parts of the World. The results of this experience have been incorporated into TRRL Road Note 40⁴¹, which gives guidelines for carrying out axle-load surveys, using the weighbridge, on paved roads in developing countries.

4.3.2 Heavy vehicle simulator: An important development in the field of pavement engineering in recent years has been the building of four Heavy Vehicle Simulators (HVS) in South Africa³⁷. Whilst the contribution these machines are likely to make to the advance of pavement design is of world-wide interest, the fact that they will be used, initially at least, in the sub-tropical climate of South Africa, will be of special interest to those concerned with improving pavement design in developing countries in the tropics.

Repeated loading tests of pavement materials at laboratory scale as described by Brown⁵⁷ has an important part to play in the development of a dependable analytical method of pavement design. However, many research workers believe that the essential validation by full-scale experience of theoretical models based on laboratory experiments can be greatly assisted by the use of intermediate forms of testing of the 'road machine' type. Indeed some research workers believe that without this intermediate step very little further progress can be made towards a reliable mechanistic method of design.

The great asset of 'road machines' is that they apply the load to test pavements through a rolling wheel, and hence they induce the same sort of changes in the directions and magnitudes of the stresses experienced by all elements of the pavement as are experienced in normal service. Several different types of road machine have been used for pavement design research in the past, but the HVS is the first full-scale machine that can be moved easily from place to place and can be used to load *in situ* both ordinarily-constructed roads as well as specially-built full-scale experimental roads and pilot scale pavements.

The HVS can apply a load of up to 100 kN through a dual or single wheel assembly which is traversed over the pavement for a distance of 8m at a speed of up to 14 km/hour. The wheel assembly reciprocates in a heavy steel frame and can apply up to 1400 repetitions of load per hour to the pavement under test. It is thus possible to apply half a million repetitions of load to a pavement in 20 to 30 days.

The prototype HVS has been in use for some time and some limited but useful results have been obtained. It has been used to verify a model that predicts the initiation of traffic-induced cracking in cement-treated road-bases. The HVS proved to be successful for this purpose and it enabled load equivalence factors for a limited number of examples of this type of pavement to be studied⁴². It was found that a 'power law' of 6.0 to 6.7 applies to such pavements, as opposed to the power of 4.0 to 4.5 that has been generally assumed hitherto. This result has considerable significance for pavement engineering in tropical developing countries where cement bound materials are more commonly used for roadbases than in most industrialised countries.

4.3.3 The design of bituminous surfacings for high service temperatures: The large increase in recent years of the length of road in tropical developing countries that requires a premixed bituminous surfacing has focused the attention of highway engineers on the need to improve the design of surfacings for tropical conditions. For many years bituminous surfacings of the asphaltic concrete type have been widely used in hot climates, and the mix design procedures for achieving high stability mixes are well-established. Experience has shown, however, that such mixes, whilst having a high resistance to deformation, are prone to cracking and are difficult to compact. It is now recognised that even for high temperature service conditions high stability is not all-important, and that more attention should be given in designing mixes to the properties of flexibility, durability and workability. The high stability of asphaltic concrete is mainly dependent on aggregate interlock and inter-particle friction which are enhanced by the careful proportioning of coarse and fine aggregates to produce a continuously graded mixture.

In Britain, with its temperate climate, such mixes have never been popular and virtually all heavy-duty bituminous wearing courses are composed of a gap-graded type of mix known as hot rolled asphalt. In effect this is a stone-filled sand asphalt in which the stiffness of the sand-filler-binder mortar provides the overall stability of the mix. Whilst such mixes are more prone to deformation than continuously graded mixes, they are more tolerant of variations in mix composition, more flexible, and easier to compact. At British temperatures gap-graded mixes have proved to be very satisfactory, and interest is growing in the use of such materials for road surfacings in the tropics⁴³. It has been found that modified forms of hot-rolled asphalt can be produced with adequate stability to resist deformation at high temperatures without sacrificing the advantages of this type of mix^{28,44}. To enhance the stability of these mixes it is desirable to use a stiffer bitumen (60/70 pen, or 40/50 pen if available) than that normally used for asphaltic concrete (80/100 pen). The problems of mix design for both gap-graded rolled asphalt and continuously-graded asphaltic concrete are fully discussed in reference 58.

For less-heavily trafficked roads in developing countries, which nevertheless require a premix bituminous surfacing, bitumen-macadams are being used successfully. Dense bitumen-macadam is virtually the same as asphaltic-concrete except that it has a rather higher voids content. Open-textured bitumen-macadams, however, have a much higher voids content and are permeable. For situations where impermeability is not required they provide a low-cost mix which is easy to make and lay, and which has a wide tolerance to variations in mix composition. They are thus well suited for overlaying lightly trafficked roads that still retain an impermeable surface but require a levelling or friction course.

In many developing countries the most economic and appropriate surfacing for the majority of paved roads is a single or multiple surface dressing⁴⁵. Unfortunately in many countries the difficulty in achieving adequate control of the surface-dressing process means that the lives of surface dressings are much shorter than they could be. Great difficulty is experienced in maintaining binder distributors so that they can apply an even film of binder at the required rate of spread. Similarly it is very difficult to maintain adequate standards of aggregate size, shape, and cleanliness. Some of the effects of these deficiencies can be minimised by such techniques as the pre-treatment of the chippings with a light coating of tar, creosote or diesel to suppress dust and to aid adhesion. Deficiencies in binder distribution are virtually impossible to counter, though they can be mitigated to some extent by the application of a light 'fog-spray' of binder and a sprinkling of sand or rock dust after the chippings have been spread on the main binder film. This technique has value whether or not the main binder film has been sprayed satisfactorily.

Slurry seals⁴⁶, used either alone or in conjunction with a surface dressing, provide very satisfactory surfacings for medium and lightly trafficked roads in many developing countries.

4.3.4 Overlay design: There is no difference in principle between the process of designing strengthening overlays for roads in developing countries and in industrialised countries⁴⁷. There are, however, differences in the appropriate methods to use for assessing residual pavement strength and in the stiffnesses of the pavements being strengthened.

In developing countries Benkelman beams are very appropriate for assessing the residual strength of existing roads. More sophisticated equipment such as the deflectograph can equally well be used, but in many cases the cost of such equipment and the difficulty of servicing and operating it in remote areas, will outweigh the advantages it offers as compared with the use of deflection beams. It has been found that well-trained teams equipped with two deflection beams and a loaded truck can achieve rates of survey adequate for a typical road strengthening programme in a developing country, and survey techniques have been developed for this purpose⁴⁸.

The effect of temperature on the stiffness of bituminous materials needs to be carefully considered when undertaking deflection surveys in the tropics. For example, in Britain it is recommended that deflection measurements are not made when road surface temperatures rise above 30°C, and all measurements of deflection are corrected to their equivalent value at a standard reference temperature of 20°C. In many developing countries road surface temperatures rarely, if ever, fall below this temperature in daylight hours, thus it is necessary to establish by investigation, the typical local deflection/temperature relationships and to select the appropriate standard reference temperature.

Tentative deflection criteria relating deflection to the subsequent traffic-carrying ability of the pavement have been suggested for typical developing country pavements²¹. Further research is needed to extend and validate these criteria in different conditions. The thickness of overlay required to reduce pavement deflections to the required 'design' level is best established by local experience, but if this is lacking the curves derived from British experience⁴⁹ can be used as a guide, suitably modified by judgement to take account of differences in materials and service conditions⁵⁰.

4.3.5 Impact (square) rollers: The idea of an impact roller was first considered in the 1930s and five-sided prototype machines were built in the early 1950s. Although these machines were used successfully in the 1960s⁵¹ to compact material in thick layers, the machines were impractical because of the problems created by the widely fluctuating loads at the drawbar. The Council of Scientific and Industrial Research (CSIR) in South Africa⁵² have studied and solved these problems and have developed a four-sided 'square' roller of 8000 kg or 10 000 kg weight. Its compactive effort is derived from the energy of the mass falling from the corners to the faces whilst being towed at about 12 km/hour. This compactive effort is many times greater than that obtained from the static mass of the roller. The roller can be raised free of the ground onto carrier wheels to pass over bridges or culverts which might be damaged by the impact blows.

The main advantage of impact rollers is their ability to compact non-cohesive materials in thick layers and at low moisture contents. A considerable amount of experience has now been gained in the compaction of uniform Kalahari sands with impact rollers. It has been shown that these rollers are very effective in compacting material below 0.5m and up to depths of 4m below the surface. The upper 0.5m may sometimes be loosened by the impact compaction process, and must subsequently be compacted by other machines. In very loose materials compaction may have to be carried out through a blanket layer of more cohesive material.

In a series of tests⁵² to compare the effectiveness of impact and vibratory rollers on a uniform marine sand it was suggested that the depth influence for the impact roller was about 3m compared with 1.8m for the 4500 kg vibratory roller and 2.2m for the 9000 kg vibratory roller. It has also been suggested that a 15 000 kg vibratory roller may give a performance comparable to a 10 000 kg impact roller.

The main disadvantage of impact compaction is the surface deformations produced by the roller and the loosening of the top layers in certain materials. For this reason this compaction technique is only suitable for earthworks and subgrade preparation and not for the compaction of pavement layers.

5. CONCRETE ROADS

Concrete roads are uncommon in developing countries for a variety of reasons. For instance in many countries cement has been in short supply for many years and road construction projects are often long distances from the nearest cement factory. Hence cement, if it is obtainable, is likely to be relatively very expensive by the time it is transported to site. Also in developing countries the construction of roads in stages makes sound economic sense, and concrete construction is not well-suited to stage construction. Furthermore, the advantages of concrete pavements over flexible pavements are most marked on weak subgrades, whilst in general, subgrades in tropical developing countries are relatively strong.

For these and other reasons very few concrete roads have been built in developing countries. On the other hand, the rapid rise in the price of bitumen in recent years may prompt a renewed interest in concrete road construction in those countries that have adequate supplies of cement. It is also possible that more concrete roads may be built if they prove to be well-suited to labour intensive methods of construction, as seems possible.

6. ASSESSING RISKS

6.1 *Decision making*

Formal decision analysis is not widely used in highway engineering, nor indeed in civil engineering as a whole. This may be because in most civil construction much emphasis is placed on design against failure, rather than on design for the optimum use of available resources. This attitude is perfectly legitimate in cases where the failure of a structure would be catastrophic, such as the failure of a dam or a major bridge. There are other types of civil engineering construction, however, in which 'failure', if it occurs, is not catastrophic, and the costs of accepting different levels of risk of failure can be quantified and should be inherent in the design process. Highway pavements are in this category since pavement 'failures' rarely have disastrous economic or social consequences, and seldom result in a road becoming completely unusable by vehicles. Indeed even the definition of the 'failure' of a road

pavement is very arbitrary, and is usually expressed in terms of a certain degree of cracking or surface deformation. Formal decision analysis, which provides a means of balancing technical and financial risks, should therefore be part of the pavement design process. In the process it may be necessary to make subjective as well as quantitative assessments of uncertainties⁵³, but this is much better than ignoring entirely the lack of precision that is inherent in pavement engineering, and it is likely to result in a more efficient use of the available resources.

6.2 *Improved forms of contract*

In most developing countries road construction is undertaken both by direct labour and by contract. The proportion of the total that is carried out by contract varies considerably from country to country, depending on the size and efficiency of the direct labour organisation and the magnitude of the national road construction and maintenance programme.

The traditional forms of contract used in industrialised countries are often inappropriate for road construction projects in developing countries, where the degree of uncertainty about many aspects of a project may be high. High risks mean high contract prices, and clearly it is in the clients' interest to apply a system of contract that can operate efficiently and fairly in a situation of uncertainty without incurring excessive costs. Recent research⁵⁴ that has been undertaken on appropriate forms of contract for use in conditions of uncertainty is particularly relevant to road construction in developing countries. This research indicates that an adaptation of the target price form of contract is likely to be most suitable. Target price contracts are essentially cost-plus contracts with specific incentives built into them to encourage all parties to reduce costs. The form of contract tends to compel the client to make a detailed appraisal of the true objectives of a project and the risks likely to be encountered in its execution. Such an approach is likely to focus the client's attention on policy issues such as the appropriateness of specifications and the use of low-grade materials.

7. FUTURE NEEDS

There is an urgent need to improve knowledge of the many factors that influence the cost of transport on earth and gravel roads in developing countries. Better knowledge is required of the interaction between vehicles and the roads on which they run, with a view to balancing both vehicle design and road design so as to minimise total transport costs. Improved quantification of the rates of deterioration of earth and gravel roads is necessary in order to assess maintenance needs in economic terms, and to plan cost-effective maintenance strategies. In quantifying the rates of deterioration of unsurfaced roads it will be necessary to separate the effects of traffic and climate, and to define better those surface characteristics of unpaved roads that have the greatest influence on vehicle operating costs. The influence on total transport costs of the method of construction of roads, whether plant-intensive, intermediate, or labour-intensive, also merits investigation.

In the field of paved roads the development of an improved method of pavement design appropriate to developing countries in the tropics is certainly needed. Initially the extension of the existing methods will no doubt be undertaken, assisted by laboratory-scale studies of pavement materials and full-scale pavement studies using accelerated loading devices such as the heavy vehicle simulator. In the longer term, however, a universal analytical method of pavement design is required, sufficiently well calibrated to enable it to accommodate the wide range of environmental conditions and materials that are encountered in developing countries⁵⁵.

The interaction between initial construction standards and subsequent maintenance merits further attention, as does the extent to which maintenance can counter pavement deterioration. There is also a need to develop appropriate specifications for locally-occurring road-building materials, many of which may not meet existing specifications, but are nevertheless quite capable of providing satisfactory service.

In conclusion, it is necessary for pavement engineers in developing countries to think more in terms of the design, construction, and maintenance of road pavements as being parts of a system, all parts of which interact with each other and with the vehicles that use the roads. The function of the pavement engineer is to manage this system in such a way that the service the system supplies to the community over a period of time is as cost-effective as possible.

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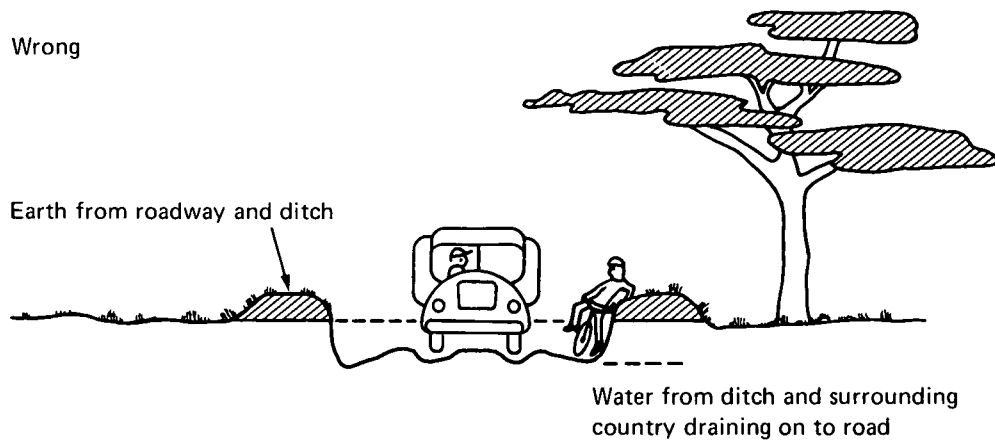
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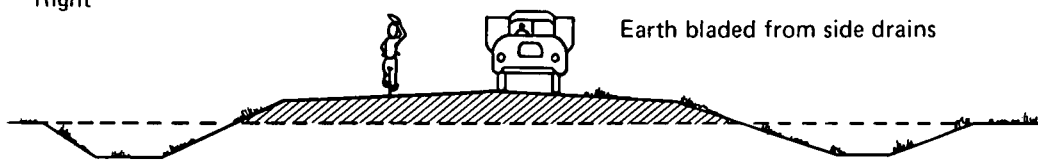
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Wrong



Typical sunken road

Right



Properly maintained earth track

Fig. 1 CORRECTLY AND INCORRECTLY MAINTAINED EARTH TRACK

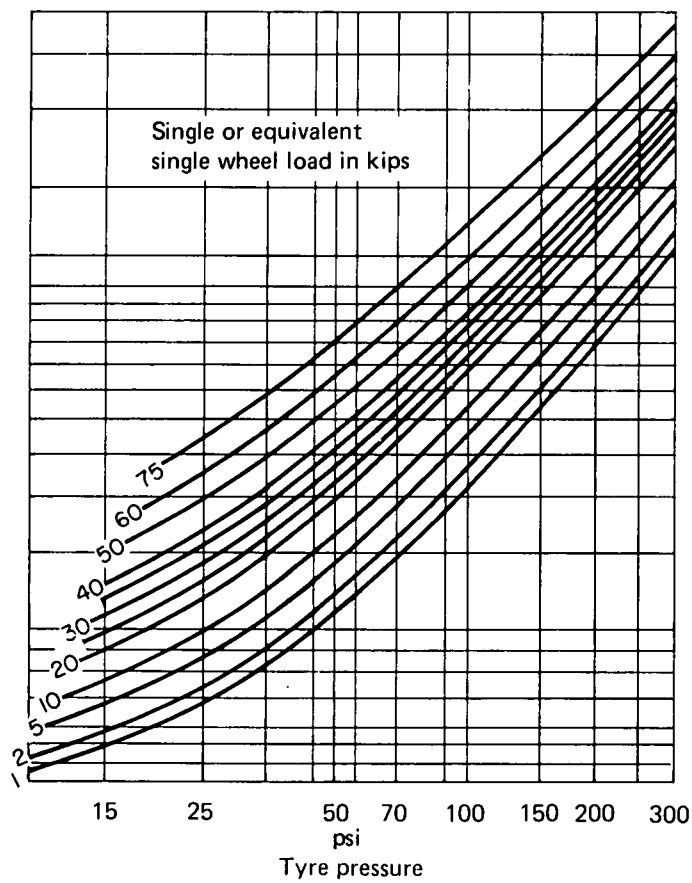
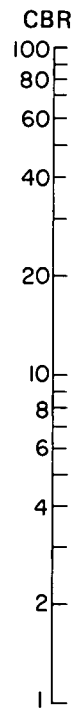
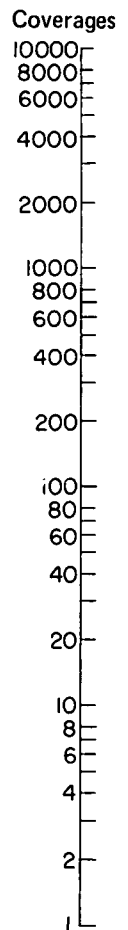


Fig. 2 RELATION BETWEEN LOAD, REPETITION, TYRE PRESSURE AND CBR FOR UNSURFACED SOILS (after Ahlvin and Hammitt¹⁶)



This scale should be redrawn 27 mm to the right before the nomogram is used.



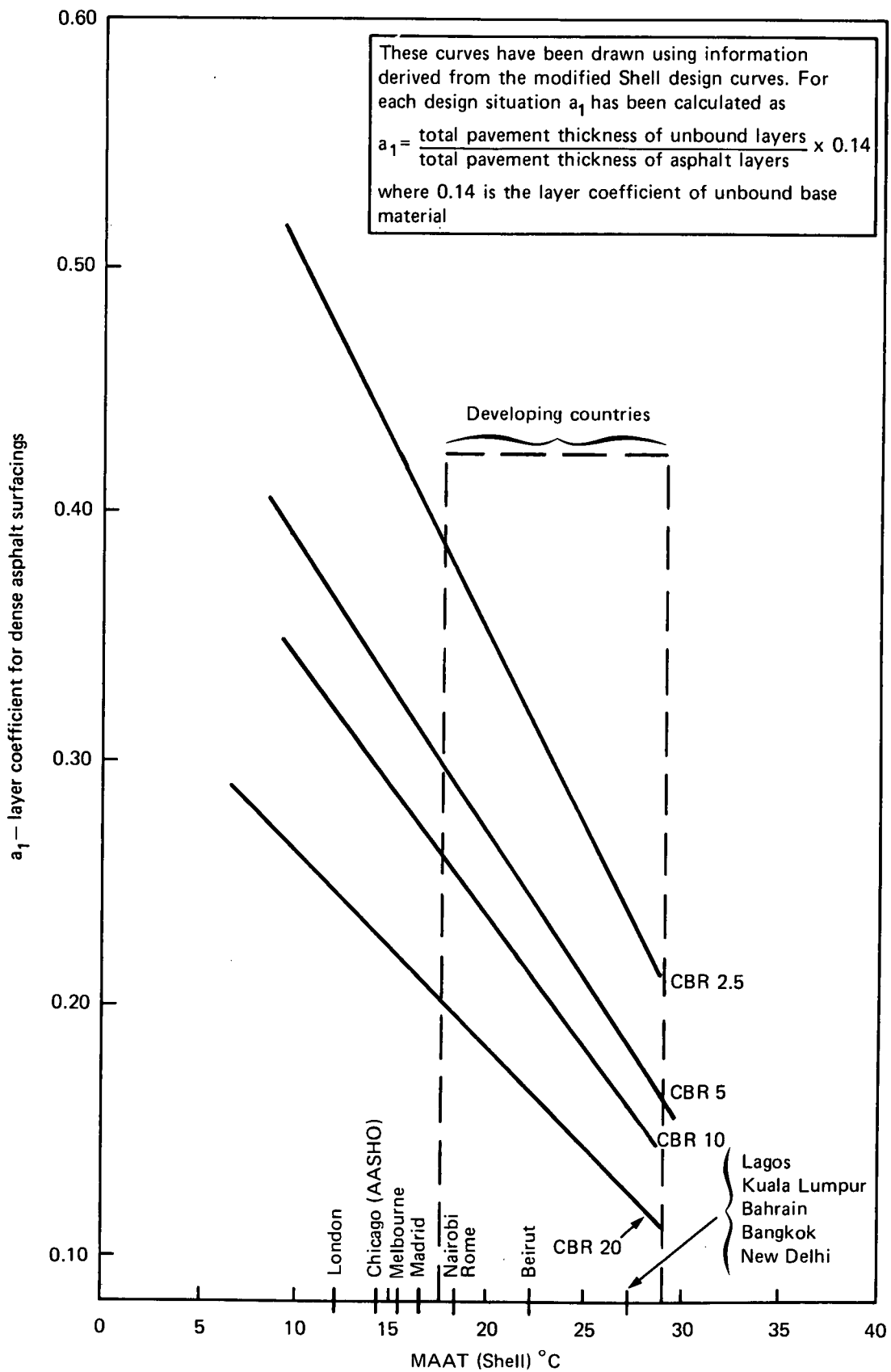


Fig. 3 POSSIBLE VARIATIONS IN SURFACE LAYER COEFFICIENTS FOR DIFFERING CONDITIONS

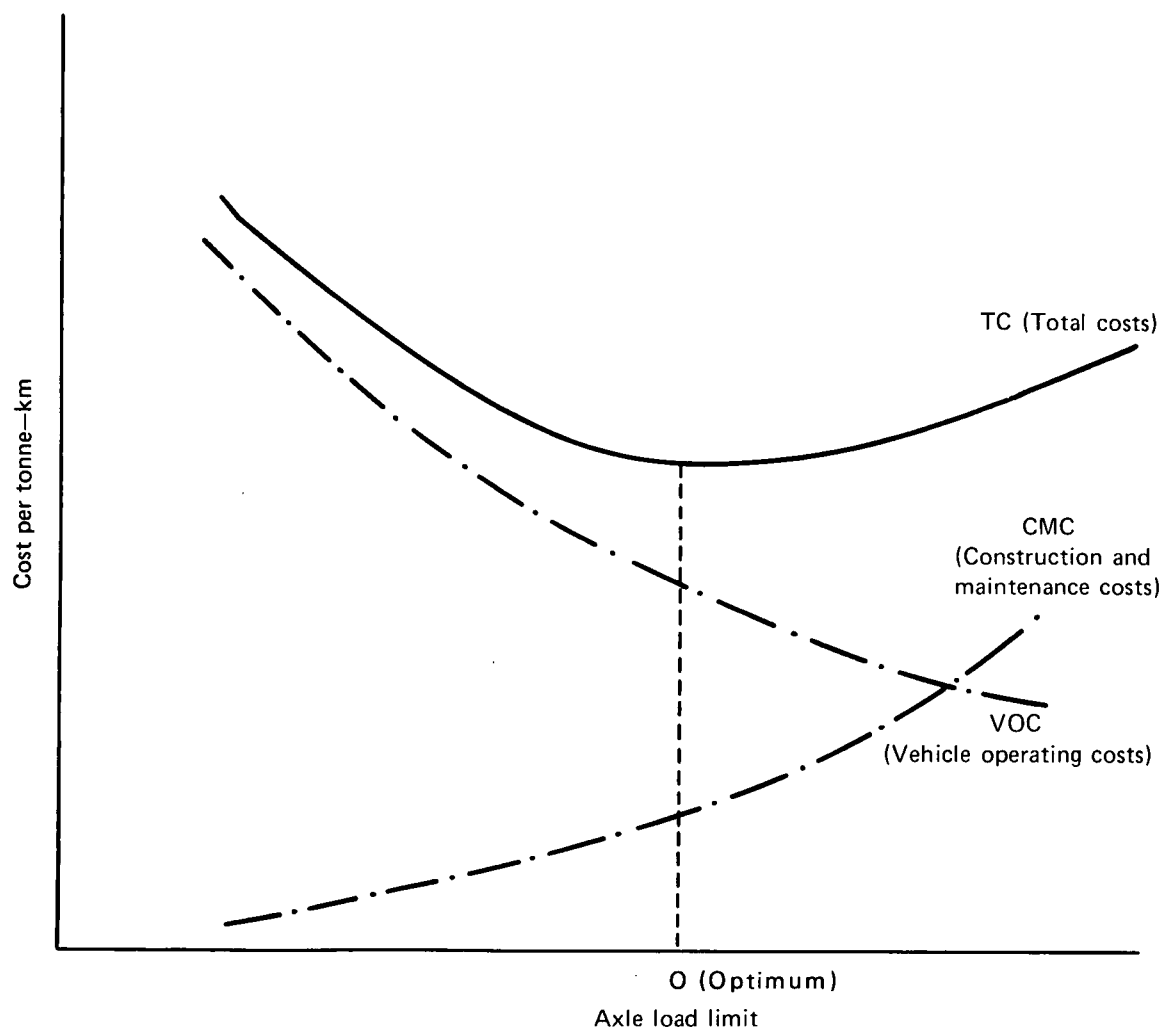


Fig. 5 THE NATURE OF THE RELATION BETWEEN TONNE-KM COSTS AND AXLE LOAD

ABSTRACT

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The importance of earth and gravel roads in developing countries is emphasised, and commonly used methods of pavement design for bitumen surfaced roads are described and compared. Recent developments in techniques and equipment for improving construction standards and for assessing road performance are described.

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