A road transport investment model for developing countries

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INTRODUCTION

In developing countries investment in rural and inter-urban roads continues to represent a large part of national development programmes. It is therefore important that decisions about such investments are made on the basis of the best possible information. The economic consequences of building roads to particular geometric and structural standards are rarely adequately investigated at project appraisal stage, largely because knowledge of the interaction between the various factors involved is very limited. Usually a set of geometric and structural standards for a road is adopted arbitrarily, and little attention is given to the effect on vehicle operating costs that the choice of alternative design standards would have.

In 1968 the World Bank wishing to improve the quality of investment decisions in the roads sector in developing countries, invited the United Kingdom Transport and Road Research Laboratory (TRRL) to participate in a co-operative research effort to investigate the inter-relationships between road construction costs, vehicle operating costs, and road maintenance costs in developing countries. These relationships were to be incorporated in a computer model that would enable road planners and designers to determine with ease the sum of these costs for a particular road investment proposal.

TRRL readily agreed to co-operate in the proposed research because much of its work for developing countries is concerned with these issues.

As a first step the World Bank awarded a contract to a research group at the Massachusetts Institute of Technology to construct a model on the basis of existing published knowledge that would relate road construction and maintenance costs to the cumulative cost of vehicle operation over the design life of a road. [1] [2] This "highway cost model" was a considerable advance on existing methods of road investment appraisal for developing countries, and it identified quite clearly the areas where knowledge about the relationships between important parameters of road and vehicle behaviour in tropical developing countries was inadequate. In particular it was clear that better information was needed on the rate and characteristics of road pavement deterioration, and the influence of road maintenance on pavement deterioration. Equally importantly the model showed that vehicle operating costs were likely to be very sensitive to vehicle type, road geometry, and road surface condition, and yet knowledge of the relationships between these factors was very limited.

Accordingly a research programme was jointly planned by the World Bank and the TRRL with the objective of improving knowledge of these relationships through field experimentation and survey in a developing country. This research programme, which included the production of a revised model, was undertaken by the TRRL in the period 1971 to 1974. During this period a wide-ranging study of road deterioration and vehicle operating costs was undertaken in Kenya to determine relationships for incorporation in the revised model more appropriate to the physical and economic conditions of developing countries. The new computer model, which has been called the Road Transport Investment Model (RTIM), calculates for any road project the sum of the construction costs, the road maintenance costs, and the vehicle operating costs over the "design life" of the project. There is considerable interaction between these costs; vehicle operating costs are a function of the volume and composition of the traffic, the geometric design standards of the road and its surface condition; road maintenance costs are influenced by the condition of the road surface, which is in turn dependent on the initial construction standard, the environment, the volume and character of the traffic.

The model therefore permits the designer to minimise the sum of construction costs, maintenance costs, and vehicle operating costs by enabling him to select the optimum choice of geometric standard and road type, either earth, gravel or bituminous surfaced.

Clearly there are many reasons for investing in roads in developing countries other than to acquire the benefits of savings in vehicle operating costs and road maintenance costs. In the case of low-volume roads in rural areas vehicle operating costs are usually a relatively insignificant factor in influencing investment decisions. Much more important factors in such situations are the provision of basic access in order to allow agricultural development projects to be instituted, or health and education services to be improved, or the general social well-being of rural populations to be enhanced.

Nevertheless at vehicle flows of more than about 100 vehicles per day, savings in vehicle operating costs and road maintenance costs are usually the predominant economic benefits that are identified as accruing from non-urban road investments in developing countries, and the greater part of the funds allocated to road construction in developing countries in recent decades has been invested on this basis. The growing interest of Third World governments and aid donors in stimulating rural development in developing countries will clearly place more emphasis on the provision of low-volume rural roads in the future, but even so, investment in the construction or upgrading of more heavily trafficked roads is unlikely to diminish.

THE FIELD RESEARCH

The field research in Kenya consisted of three distinct studies:

a) A study of the rate of deterioration of paved and unpaved roads, taking into account the influences of initial standard of construction and subsequent road maintenance on deterioration rates.

b) A study of the effect of road geometry and surface condition on vehicle speeds and vehicle fuel consumption.

c) A survey of typical vehicle operators to obtain information on the components of vehicle operating cost other than fuel.

These studies have been fully described earlier. [3] [4]

In the first two studies a programme of detailed measurements of road deterioration, vehicle fuel consumption and vehicle speed were made on selected 2 km-long sections of normally-constructed road. These test sections were selected so that the effects of road geometry, pavement type, rainfall and maintenance input could be studied. The sampling frame included three levels of vertical and horizontal road geometry, two levels of an-

Table 1 Classification of paved road test sections

	Geometric Classification	Low rainfall < 1000mm/year			High rainfall > 1000mm/year		
	Vertical / Horizontal	Flat <1.5%	Intermediate >1.5% <3.5%	Steep >3.5%	Flat	Intermediate	Steep
Old surface-dressed roads (OB)	Low <30°/km	OB17* OB18	OB20* OB24	OB21 —	OB7* OB10	OB5 OB11*	OB2 OB3*
	Medium >30°/km <90°/km	OB23* OB25	OB19* OB22	— —	OB8* OB9	OB13 —	OB1* OB4 OB14 OB16
	High >90°/km	— —	— —	— —	— —	OB6 —	OB12 OB15*
New surface-dressed roads (NB)	Low	NB10	NB12	NB13	NB2	NB4	NB3
	Medium	—	NB11	NB14	NB1	NB9	NB8
	High	—	—	—	NB5	NB6	NB7
Premix surfaced roads (P)	Low	P8	—	—	P2	P7	P6
	Medium	P10	—	—	P3	P1	P4
	High	—	P9	—	—	—	P5

Note: The asterisk* indicates a nil maintenance section.

Table 2 – Classification of gravel and earth road test sections

	Geometric Classification	Low rainfall ≤1000mm/year			Hig rainfall >1000mm/year		
	Vertical / Horizontal	Flat ≤1.5%	Intermediate >1.5% <3.5%	Steep ≥3.5%	Flat ≤1.5%	Intermediate >1.5% <3.5%	Steep ≥3.5%
Gravel sections (G)	Low <30°/km	G22(N) G28(I) G29(Z) G41(N)	G21(N) G26(N) G31(I) G32(Z)	G24(N) G33(N) G35(I) G36(Z)	G4(I) G8(Z) G9(N)	G5(I) G7(N)	G12(N) G13(I) E2(N)**
	Medium >30°/km <90°/km	G30(N) G42(Z)	G34(N) G38(I)	G20(N) G25(I)	G1(I) G2(N)	G3(I) G10(Z) G11(N)	G6(N)
	High >90°/km	G40(N)	G16(N)	G23(N)	—	G17(I)	G18(I) G19(Z)
Earth sections (E)	Low <30°/km	G27(N)*	—	—	—	E1(N) E3(I) E4(Z)	
	Medium >30°/km <90°/km	G37(I)* G39(N)*	G15(I)* —	—	—		—
	High >90°/km	—	—	G14(N)*	—	—	—

Notes:
(N) Normal maintenance level
(I) Intermediate maintenance level
(Z) Nil Maintenance level
* These sections were originally gravel sections but were reclassified as earth sections because the particle size distribution was poor.
** This section was originally an earth section but was reclassified as a gravel section.

nual rainfall and four road types as follows:

(i) gravel-surfaced roads;

(ii) recently built roads with cement-stabilised bases and bituminous surface treatments;

(iii) older roads with cement-stabilised and bituminous surface treatments;

and

(iv) roads with crushed stone bases and asphaltic concrete surfacings.

This frame provided 72 cells, many of which were sub-divided into two or three different levels of maintenance, to allow the effect of road maintenance on deterioration to be studied.

In practice it proved impossible to find sections of road to fill every cell, and the experiment actually embraced 95 test sections of road, 49 of which were paved and 46 unpaved. Tables 1 and 2 show the sample frames for the paved and unpaved roads.

On each of the test sections measurements were made of the strength, grading, moisture content and thickness of the pavement layers, the surface irregularity (roughness), the depth of rutting and the rainfall. On unsurfaced roads the looseness and rate of loss of the gravel surface were also measured. In addition the volume and composition of the traffic, the average vehicle speeds, the weights of vehicles and their axle loads, were recorded. Finally the fuel comsumption of specially instrumented vehicles was measured as they traversed the test sections at different speeds. All these measurements were repeated at regular intervals over a period of three years, during which time the condition of many of the test sections deteriorated significantly.

The methods of measurement used were kept as simple as possible. [5] Standard tests were used for the pavement evaluations, such as the CBR test, deflection tests and standard soil tests. Surface irregularity was measured, both with a standard BRR roughometer [6] (or '5th wheel bump integrator') and a simple vehicle-mounted bump integrator. On the gravel road sections gravel loss was recorded by levelling surveys and the looseness of the gravel was measured by recording the quantity of loose material that could be swept up by hand from a given area. Vehicle flows were recorded with simple automatic traffic counters and vehicle speeds were measured using two synchronised stopwatches operated by observers stationed at each end of the test sections. Vehicles were weighed using a portable weighing unit specially developed by TRRL for use in roadside axle-load surveys in developing countries. [7] Fuel consumption was measured by a simple volumetric displacement device fitted to the three test vehicles that were used for the series of controlled fuel consumption experiments.

The highest average daily traffic encountered on any of the test sections was less than 1500 vehicles per day, hence at all sites free-flow traffic conditions prevailed.

The survey of vehicle operators was conducted to gather information on those elements of vehicle operating cost that cannot be satisfactorily investigated by measuring experimentally the operating characteristics of a small number of instrumented vehicles. These are vehicle maintenance costs, tyre costs, vehicle depreciation costs, crew wage costs and the cost of lubricants consumed. Information on these costs was collected from a variety of vehicle operators, ranging from one-vehicle owners to companies operating a large number of vehicles. Detailed information was collected on nearly 300 individual vehicles ranging from motor cars to 26-ton lorry/trailer combinations, whose ages ranged from new vehicles to some that had covered over one million kilometres. In addition information was collected about the routes on which these vehicles normally ran. The geometric characteristics of these routes were measured from large-scale maps, and the road surface roughness of the routes was estimated from sample measurements with a 5th wheel bump integrator.

Subsequent to the field research in Kenya, further research into vehicle operating costs has been untertaken in Ethiopia, [8] Scotland and Ghana to extend certain of the relationships and to investigate their validity in other environments.

THE MODEL

On the basis of the field studies a series of relationships were derived that enable the construction costs, road maintenance costs, and vehicle operating costs for a specified road to be calculated, taking account of the very considerable interaction that exist between these costs.

The relationships were incorporated in a model, called the Road Transport Investment Model (RTIM)[9], which calculates these costs for each year of a road's "design life", adds them together and discounts them back to a base year at a given discount rate. For a given road project the model can calculate this "total transport cost" over an analysis period of up to 24 years.

The model operates in terms of physical quantities to which any desired system of costs and prices may be applied. Costs can thus be presented in terms of any desired currency, provided the unit rates are input in the same currency.

The model also has the facility of analysing the cost consequences of a variety of stage construction policies. Many options can be examined, such as upgrading an earth road to a gravel or paved road either on an existing or on a new alignment, the widening or overlaying of a road pavement, or the complete reconstruction of a pavement.

The model is designed to operate with the same sort of basic input information as is normally collected by a team of engineers and economists undertaking a feasibility study for a non-urban road project in a developing country. The model is thus conceived essentially as being a tool to assist and improve the quality of the execution of such feasibility studies.

The basic inputs required to operate the model are as follows:

a) route location;
b) road design standards;
c) terrain information;
d) properties of construction materials;
e) construction unit costs;
f) environmental factors;
g) unit costs of vehicle operation;
h) traffic volumes;
i) traffic composition;
j) vehicle loads;
k) road maintenance policy; and
l) road maintenance unit costs.

An outline flow diagram of the model is shown in Figure 1. A typical run of the model begins with construction. In each year in which construction or reconstruction occurs, the model calculates the quantities and hence the costs of earthworks, pavement, drainage and site clearance. The deterioration of the road surface is then estimated as a function of the initial construction standard, the maintenance policy selected, the rainfall and the traffic flow. An estimation of the average speeds of different vehicle types is then made, based on the previously estimated road surface condition and the geometric characteristics of the road.

Fuel consumption, tyre wear, vehicle maintenance and depreciation costs are then calculated and applied to the traffic forecasts to produce the total vehicle operat-

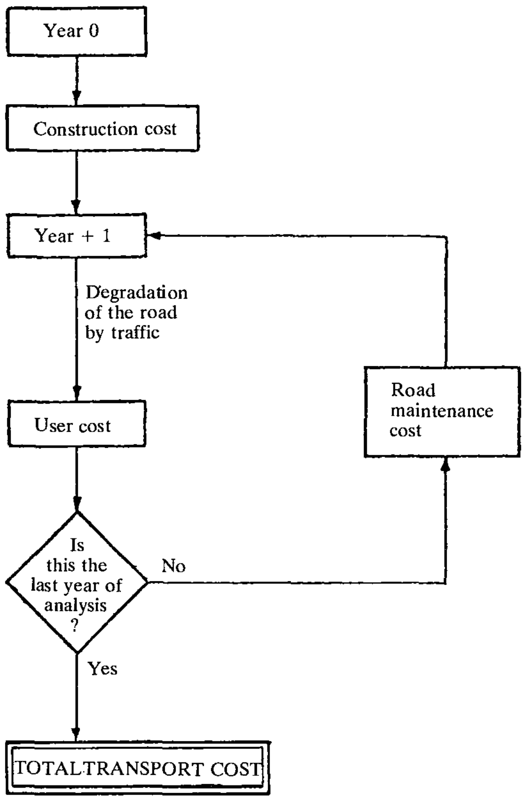

Fig. 1 - Framework for determining total road transport cost

ing costs for the year in question. An option is available to calculate time costs based on values of time that must be input into the model. Road maintenance costs also depend on the condition of the road and thus they are also estimated for each year of the analysis period on the basis of the predicted road surface condition.

At the end of each year the road condition and the traffic volumes are compared with the values set by the User as being those at which upgrading or reconstruction should take place. If required these operations are costed and the condition of the upgraded or new road thus specified is taken into account in the subsequent year-by-year analysis. Figure 2 is a flow diagram showing the upgrading and maintenance options available in the model.

If desired parts of the model can be used independently. For example it is possible to calculate construction quantities and costs for a new scheme without considering vehicle operating costs or road maintenance costs. Similarly the model can be used to analyse the pavement deterioration, user cost, and maintenance cost of an existing road, without activating the construction cost sub-model: this is very useful for analysing the consequences of upgrading an existing road.

The model does not attempt to calculate any of the benefits that might accrue from a road investment other than those that derive from vehicle operating cost or road maintenance cost savings. Hence in undertaking a feasibility study other benefits, such as increases in agricultural production or other quantifiable increases in economic activity, must be estimated separately. The model also does not calculate the commonly used indicators of economic viability, such as net present value, benefit/cost ratio, internal rage of return etc. However, the output is in such a form that the information from each separate run can easily be used to calculate these indicators. Similarly, when the introduction of a new or improved road leads to induced traffic, the output from a "do nothing" run and a "do something" run can easily be combined to calculate the benefits for this type of traffic. The model does not optimise in the strict sense of the term, it simply determines the total transport cost of a series of options that must be specified by the User. It was felt desirable to retain this dependence on User/model interaction for seeking the minimum cost solution so that the road designer maintains adequate control of the selection of options that are investigated.

METHOD OF OPERATION

Vehicle and traffic input data

The model can consider separately up to eight classes of vehicle, passenger cars, light commercial vehicles, buses and up to five classes of heavy commercial vehicles. In the case of the heavy vehicles, the degree of loading and axle load equivalence factors for the five classes are required to be input to the model, and if desired the loading and axle load equivalence factors can be different for the traffic travelling in each direction. Traffic growth forecasts must be made for each vehicle class over an analysis period of up to 24 years. The vehicle speed relationships in the model assume "free flow" conditions, and hence if traffic growth is such that speed reductions caused by congestion begin to occur during the analysis period, a warning message is printed in the output to inform the User that a separate analysis outside the model will be required.

Geometric design and ground input data

The vertical alignment can be specified in terms of the intersection points of tangent lines and the vertical curves that connect the tangents. If no vertical alignment has been designed the model will produce a design using a method based on that of program VENUS. [10] The required standards for maximum gradient and minimum radius of vertical curvature must be input into the model. If these standards are violated the model will automatically adjust the vertical alignment to ensure that it complies with the required design standards.

Ground information is specified to the model in terms of centre line levels and crossfalls at stations along the centre line. Alternatively grounds levels may be given at two offsets at each station. If only contour maps are available stations may be specified whenever the centreline crosses a contour.

The vertical alignment and ground data are of course used by the model to calculate earthworks quantities, but the model also uses the vertical alignment to predict vehicle speeds and fuel consumption and the rate of loss of surface material from unsurfaced roads.

Horizontal alignment is specified in terms of the average degree of curvature per kilometre, and this is used only for the prediction of vehicle speed.

The road cross-section is defined in terms of the width and crossfall of the running surface, the width and crossfall of the shoulders, the angle of cut and fill slopes, and the ditch details. (See Figure 3) When the alignment traverses ground that slopes steeply across the roadline the model can calculate the earthworks cost on the basis that retaining walls will be used, the cost of the walls themselves being included in the calculation. The sideslope at which retaining walls become necessary must be input to the model, together with standard dimensions for the walls expressed as a function of wall height.

Construction costs

Earthworks volumes are calculated by the average-

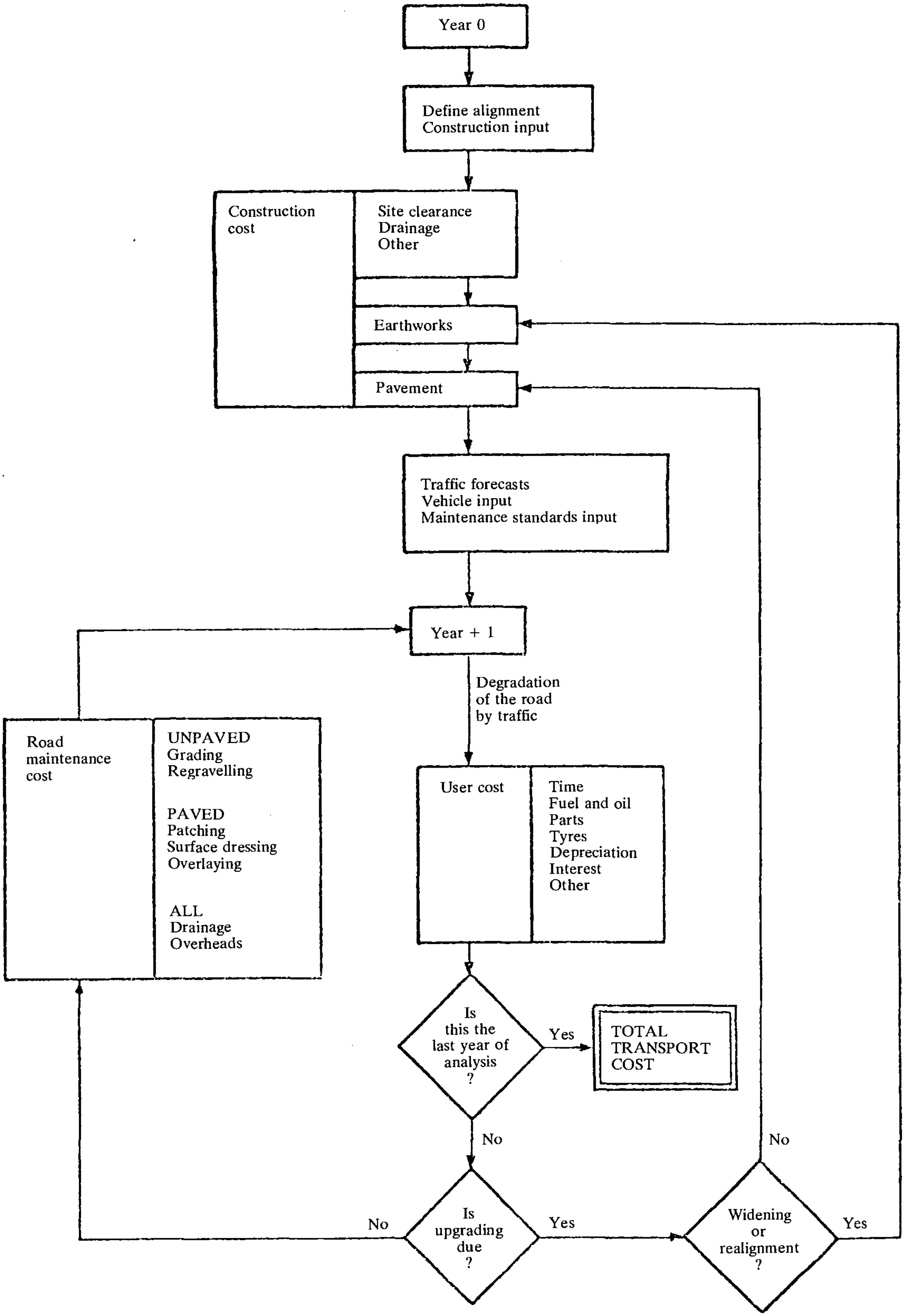

Fig. 2 - Flow chart of road transport investment model showing costs and upgrading

end-area method, cut and fill being considered separately. The unit costs of excavation, filling, hauling, borrowing and spoiling must be input to the model. The model calculates the maximum haul distance beyound which it is cheaper to borrow or spoil material rather than haul it, and then it constructs a mass-haul diagram with the balance lines so positioned that the material within the balance loops is that which can be economically hauled and the rest of the material is either spoiled or borrowed. The model calculates site clearance costs from the width of clearance specified and unit rates for clearing different types of vegetation that must be input to the model.

Pavement costs are calculated on a layer by layer basis, up to six pavement being considered by the model if required. For gravel roads only one pavement layer is considered and for earth roads none. Each layer must be specified in terms of its thickness, the type of material, and the strength of the material. The strength of sub-base material is expressed in terms of its California Bearing Ratio (CBR), base material in terms of CBR or unconfined compressive strength, and asphaltic materials in terms of strength coefficients. [11] The cost of each material per square metre or cubic metre must be input.

The shoulders, which may be earth, gravel or paved, are specified in the same way as the road pavement itself.

Three elements of drainage cost are considered by the model; the cost of cross-flow culverts for the transfer of water from one side ditch to the other, the cost of culverts for carrying streams and small rivers under the road, and the cost of bridges for larger water crossings. The cost of the latter must be specified directly, but the model will calculate the size and the cost of culverts for stream crossings provided that data on catchment areas, rainfall and unit costs of construction are input. The required spacing and size of the crossflow culverts must also be input to the model.

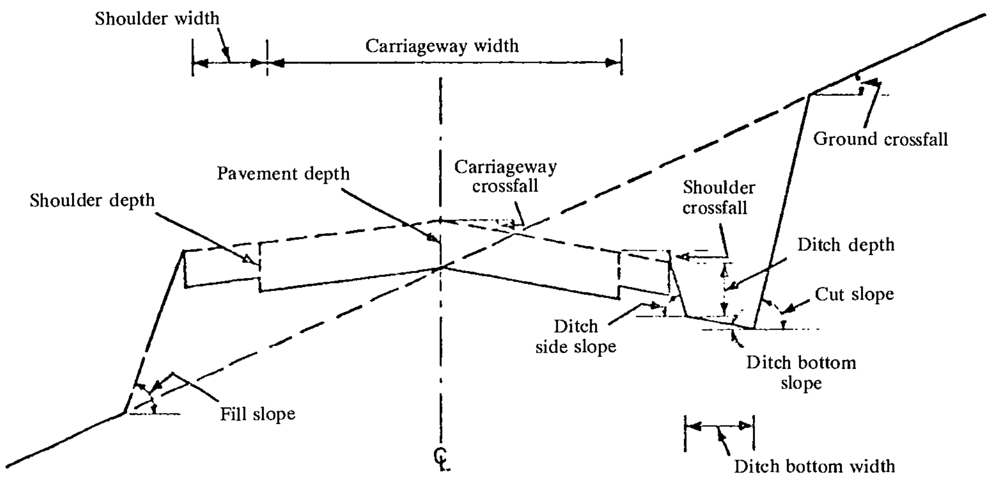

Fig. 3 - Road cross-section

Road deterioration

The model predicts the amount of deterioration of the road surface that will occur due to trafficking on a year-by-year basis. For earth and gravel roads deterioration is defined in terms of roughness, rutting, looseness of the surface, and in the case of gravel roads only, the loss of gravel. The factors that the model considers in calculating the rate of deterioration of unpaved roads are the volume of traffic, the type of surfacing material, the rainfall and the road gradient.

Paved road deterioration is defined in terms of roughness and the amount of cracking. These are functions of the pavement strength and the cumulative axle loading expressed in terms of equivalent standard axles [12] (of 8.2. tons). Using the input data on the strength and thickness of the pavement layers, the model calculates a "modified structural number" as an index of pavement strength. The model then predicts the deterioration of the road surface in each year that the road is trafficked. The deterioration relationships used by the model for both paved and unpaved roads were derived from the results of the studies in Kenya. They represent a considerable advance in knowledge about the rate of deterioration of roads in environments similar to that of East Africa, but they cannot be used with the same degree of confidence in very different tropical environments, such as those with very high or very low rainfall.

Road user costs

The sum of time costs and vehicle operating costs is determined for each year that the road is open to traffic. Time costs are calculated by multiplying the value of passenger's time by journey time. The value of passenger's time must be input to the model, but journey time is calculated within the model from the road length and the average vehicle speed.

Vehicle speed is calculated for each class of vehicle. For paved roads it is a function of the rise and fall of the road, its horizontal curvature, its width and its altitude. Similarly on unpaved roads vehicle speed is a function of road geometry, but the roughness of the road surface, its moisture content and the depth of ruts, are also significant factors.

The fuel consumption of the spectrum of vehicles that will traverse the road is calculated for each class of vehicle. On paved roads fuel consumption is a function of the distance travelled, the speed, the rise and fall of the road, and in the case of heavy vehicles, the gross weights and power-to-weight ratios. On unpaved roads the same factors are significant with the addition of the road surface roughness and surface looseness. The cost of fuel must be input to the model.

The costs of tyre consumption, spare parts and lubricating oil are also calculated for each vehicle class, all three costs being related to vehicle type and the distance travelled. Tyre costs are additionally related to the roughness of the road surface, and for heavy vehicles, to gross vehicle weight. Spares costs are related to road surface roughness and the distance covered by vehicles since manufacture, and oil costs are related to road surface type. The unit costs of new tyres, vehicles and lubricating oil must be input to the model.

The depreciation cost of vehicles is calculated on the basis of vehicle age, an initial age spectrum being assumed which is modified each year by growth and wastage of the vehicle population.

The model also calculates vehicles' crew costs, interest charges and standing costs for the vehicle population using the road under consideration. Values of crew wage rates and interest rates must be input to the model.

All road user costs may be expressed in both economic and market terms, separate accounts of these costs being kept within the model, thus enabling the User to analyse a project in either terms.

Road maintenance costs

Road maintenance costs are analysed by the model in some detail. In the case of paved roads the operations of patching, surface dressing and overlaying are considered. On unpaved roads the operations considered are grading and regravelling. Additionally on both types of road shoulder maintenance and ditch clearance are considered. The model predicts the amount of maintenance required annually on the basis of the amount of traffic the road carries. The cost of the maintenance is then calculated using unit rates that are input to the model.

Stage construction

When either the condition of the road deteriorates below a given standard, or the level of traffic grows to a "threshold" value set by the User, it may be necessary to upgrade a road. For example an earth road may need to be upgraded to a gravel road, a gravel road may need to be paved, or a paved road may need to be overlaid. The model can consider any of these stages, taking into account the costs of any widening or re-alignment that may be required in addition to the pavement costs. The effects of the upgrading on vehicle operating costs and road maintenance costs are of course allowed for in calculating the cost streams subsequent to the upgrading operation. A number of different stage-construction strategies can be evaluated by the model, thus allowing the User to investigate many possible options.

APPLICATIONS OF THE MODEL

The model has already been used to evaluate several road projects in developing countries.

Initially it was applied in retrospect to a recently completed road project in Kenya to test the functioning of the model, and to compare its estimate of construction cost with the actual contract costs. In addition the sensitivity of discounted costs to variations in the assumptions made about discount rates and traffic growth rates were examined. Good agreement was obtained between the construction costs calculated by the model and the actual contracts costs. Also at a first year average daily traffic of 400 vehicles per day, the discounted road user costs over ten years were two and a half times the cost of construction, and discounted road maintenance costs were less than one per cent of total transport costs. Total discounted transport costs were found to be very sensitive to traffic growth assumptions but relatively insensitive to road construction and maintenance costs, whatever discount rate was assumed. This case is typical of many non-urban roads in developing countries and demonstrates the value of adopting a stage-construction strategy when traffic prediction is uncertain, and the wisdom of undertaking effective road maintenance since its cost is relatively minor and its effect on the major cost of vehicle operation is substantial.

The model has also been used to evaluate road projects in Belize, Thailand, Lesotho and the Central African Republic (CAR). In each case the model proved its worth and enabled the relevant features of widely differing types of road project to be examined more thoroughly than otherwise would have been possible. For instance in the Belize project alternative routes with similar geometric standards were compared, in the CAR project the effects on total transport cost of various vertical alignment standards were investigated, and in the Lesotho project the upgrading of an existing gravel road was examined.

In use the model has been found to be easy to operate and its data requirements easy to satisfy. Some of the lessons that have been learnt from these applications are:

a) on roads carrying more than about 100 vehicles per day the total transport cost is very sensitive to road length, hence it may be worth incurring extra construction costs if the road can be shortened by so doing;

b) on gravel roads carrying more than 100 or so vehicles per day total transport cost is sensitive to the estimates made of road surface roughness; as a consequence in such cases it may not be possible to estimate total transport costs to closer than plus or minus 20 per cent for this reason alone;

c) on all but very low-volume roads total transport costs are very sensitive to the estimates of future traffic; and

d) there is a need to extend the vehicle operating cost relationships to cover roads with more extreme geometric characteristics and surface roughness, to encompass a wider range of gravel types, and to test all the relationships in other climatic and economic environments.

CURRENT DEVELOPMENT

As has been mentioned, further field research has been undertaken, subsequent to the main study in Kenya, to improve and extend several of the relationships within the model.

In Ethiopia a study of the speeds and the weights of commercial vehicles [8] has enabled the speed estimating equations for medium and heavy goods vehicles to be improved. These improved equations have been incorporated into the model, together with improved pavement performance equations. [11]

A study has been made of the fuel consumption of heavy vehicles on mountain roads in Scotland as a first stage of a programme of research planned to extend the vehicle operating cost relationships to cover roads with more severe geometric characteristics than those of Kenya.

Research on pavement deterioration and road strengthening is being continued in Kenya, the results of which will be incorporated into the model as they become available.

In parallel with this research being undertaken by TRRL, a major study of the inter-relationships between the costs of highway construction, maintenance and vehicle operation is in progress in Brazil, and a study of vehicle operating costs is being started in India. The World Bank played a key role in initiating both of these studies, the conceptions of which are very similar to that of the Kenya study. In due course it can be expected that these studies will result in models very similar to RTIM, and that they will produce relationships that may improve, complement, or extend some of the relationships currently incorporated in RTIM.

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