THE TRRL ROAD INVESTMENT MODEL FOR DEVELOPING COUNTRIES (RTIM2)

by

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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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THE TRRL ROAD INVESTMENT MODEL
FOR DEVELOPING COUNTRIES (RTIM2)

ABSTRACT

A computer model is described which is designed to aid investment decisions within the roads sector in developing countries.

The model calculates the construction cost of a road and predicts the condition of the road as time passes and vehicles travel over it. Having predicted the condition of the road, the model estimates the costs of road maintenance and the cost of operation of the vehicles for each year. All these costs are then discounted back to the base year and summed over the life of the road to obtain the total cost. All estimates are made in terms of physical quantities and costs are obtained by applying unit rates to these quantities.

The results of a study in Kenya were used to calibrate a prototype version of the model. This prototype was tested extensively for the appraisal of road projects in developing countries. As a result of this experience, the model has now been reprogrammed to make it easier to use and to fit onto smaller computers. The opportunity has also been taken to include in the model the results of the latest research in developing countries in this field carried out by TRRL.

The relationships built into the model allow it to be used to study the interrelationships between road design and construction standard, road maintenance policy, vehicle characteristics, traffic flow and growth rates, environment, and road deterioration. The model can be used to study various aspects of a road investment project such as the optimum maintenance standards for the road, the effects of providing an earth, gravel or bituminous pavement, or the differing benefits that can be obtained by adopting various stage construction options. The model will also allow the planner to study the consequences of uncertainties in traffic forecasts or in the discount rate.

1. INTRODUCTION

This report describes a computer model which is designed to aid investment decisions within the roads sector in developing countries. The model will be of assistance to senior administrators, engineers and planners, and those responsible for developing improved techniques for road investment appraisal.

When planning investment in infrastructure it is necessary to evaluate all the costs associated with the provision of the new facility. These costs include not only the first cost of the facility and its cost of operation, but also the cost of maintaining the facility throughout its 'life'. This approach to investment evaluation is especially relevant for road projects.

The costs of building and maintaining roads are usually borne by the community as a whole, finance normally being provided from national and local taxation or duties. However the costs of operation
of roads are borne by the road users themselves in the form of vehicle operating costs, the cost of time spent in travelling, and part of the cost of road accidents.

In developing countries traffic volumes are generally much lower than those in industrialised countries. Incomes, and the value attached to travel time are also generally much lower. In consequence the costs of travel time and road accidents on any particular road in a developing country are usually small in relation to the vehicle operating costs, and thus they are not very significant in the evaluation of a road investment.

When planning a road investment the objective is normally to minimise the total cost to the community. In developing countries this generally means minimising the sum of the construction, the maintenance, and the vehicle operating costs.

These costs are not independent of one another. The vehicle operating cost depends on the number and type of vehicles using the road, the type of journey that they make, the geometry of the road alignment, and the condition of the road surface. For instance, if the alignment has many steep gradients, fuel consumption will obviously be higher than for a flat road. Similarly, if the road surface is very rough, vehicle components such as tyres and mechanical parts will wear out quickly, resulting in a high operating cost.

The geometry of the road alignment directly affects the cost of construction. In hilly terrain, the cost of building wide roads with flat gradients is high. Construction costs can be reduced by building a narrower road with steeper gradients, but this will be at the expense of a higher cost of operating vehicles. Likewise the cost of operating vehicles on smooth bituminous roads is less than the cost on rougher gravel surfaced roads, but roads paved with bitumen are obviously more expensive to construct than those surfaced with gravel. Hence it is clear that there is a trade-off between road construction costs and vehicle operating costs.

The condition of the road surface, besides being affected by the construction standard, is also affected by the traffic loading, the standards (and hence the costs) of maintenance, and the environment. The more vehicles that use the road and the heavier their axle loads, the more quickly will the road wear out. The road will also wear out more quickly if it is subject to heavy rainfall which weakens the structure of the road or causes erosion. However, the rate of deterioration of the road's structure and its surface condition can be slowed down by effective and timely maintenance at intervals throughout the road's life. Thus environment, traffic, and maintenance all affect the surface condition of the road and, therefore, all have an effect on the cost and changes in cost of operating vehicles on the road (Figure 1).

In order to achieve the objective of minimising the cost of constructing and maintaining a road, and operating vehicles on it, it is necessary to know how these costs are affected by the interrelationships that have been described. A computer program has been written which makes use of these relationships to determine construction, maintenance, and vehicle operating costs over the service life of individual road links.

The report describes the operation and use of the model. Details of all of the relationships used are given in the Appendices.
2. THE PROTOTYPE TRRL MODEL

2.1 Development of the model

The first move towards producing a model of this type was made in 1968 by the World Bank when draft terms of reference for a 'Highway design study' were produced for internal consideration within the Bank. Shortly after this, the Transport and Road Research Laboratory were approached and invited to participate in the proposed study in partnership with the Bank. From this point on, close liaison was maintained between the two organisations and the next step was taken when the World Bank commissioned a group at the Massachusetts Institute of Technology to carry out a literature survey and to construct a model based on information already available. The 'Highway Cost Model' produced by MIT was a considerable advance over any other methods existing at that time for examining the interactions between road costs, maintenance costs, and vehicle operating costs. However the model highlighted areas where more research was needed to replace relationships which were inappropriate to developing country environments, and to provide additional relationships.

Accordingly the Overseas Unit of the Transport and Road Research Laboratory, with the collaboration of the World Bank, undertook a major field study in Kenya to investigate the deterioration of paved and unpaved roads and factors affecting vehicle operating costs in a developing country. The performance of more than 90 one-kilometre long test sections of road was monitored at regular intervals over a period of two years. The condition of paved roads was quantified in terms of surface roughness, depth of ruts, amount of cracking, deflection, CBR and moisture content of the various pavement layers. Pavement deterioration was related to the number of passes of an 8.2 tonne 'standard' axle load and to the strength of the pavement. For unpaved roads, deterioration was related to the gravel type and the number of vehicle passes and was measured in terms of surface roughness, depth of ruts, depth of loose surface material and the depth of the gravel surfacing layer itself. An experimental study was carried out to measure vehicle speeds and fuel consumptions over the same test sections. In addition, data were collected from many commercial vehicle operators on such items as the lubricating oil consumption of vehicles, the maintenance requirements of vehicles, tyre wear, and vehicle depreciation. Relationships were then developed relating these directly to the physical operating conditions.

The results of this study were used to calibrate a prototype computer model (RTIM) for evaluating the costs of construction, maintenance and vehicle operation for a road investment project in a developing country. An outline flow-diagram of the model is shown in Figure 2. The model calculates the construction cost of a road and predicts the condition of the road as time passes and vehicles travel over it. Having predicted the condition of the road, the model estimates the costs of road maintenance and the cost of operation of the vehicles for each year. All these costs are then discounted back to the base year and summed over the life of the road to obtain the total cost. All estimates are made in terms of physical quantities and costs are obtained by applying unit rates to these quantities.

2.2 Experience of use

The prototype version of the model was tested extensively by the Laboratory, and has been used by the World Bank, government departments, consultants, and other organisations. Although the model was relatively complex, it was nonetheless easy to use when reasonably efficient computer facilities were available and its application and data requirements were well within the capabilities of potential users. The model represented a significant advance in road planning methodology and has been used in many different developing countries.
In 1976 the World Bank instigated further developments of the computer model when they awarded a research contract to the Massachusetts Institute of Technology (MIT) to produce an extended version of the model capable of carrying out economic analysis directly, analysing a road link separated into several homogeneous sections, carrying out automatic sensitivity analyses of key variables such as discount rate and traffic growth, and requiring less detailed construction and maintenance input data than the prototype version of the model. This work resulted in the production of the 'Highway Design and Maintenance Standards model' (HDM).

However, experience gained by TRRL in the use of the prototype RTIM suggested that, rather than producing a more complex model, there was also a need for a different approach. It was found that in many developing countries adequate computer facilities were either not available at all, or were not large enough to run a program of the size of the prototype RTIM (or HDM). When large enough computers were available, difficulties were often experienced in gaining access to them. Consequently UK consultants using the model generally preferred to run the program in Britain using data sent from overseas by telex. Also, potential users in developing countries were often reluctant to use the model because of lack of familiarity with computer methods in general and, when personnel had been trained in the use of the model, staff turnovers often led to the subsequent loss of that expertise.

Some of these difficulties have been overcome by publishing the relationships which are built into the model as a book of tables. This enables users in developing countries who do not have access to computers to utilise the relationships in the model in a manual mode. In addition, as a result of experience gained in the use of the prototype in developing countries, the TRRL road investment model has now been reprogrammed to make it easier to use and to fit onto a smaller computer. An ultimate objective is to provide a version of the model for developing countries that will run on a desk-top computer.

In reprogramming the model the opportunity was also taken to incorporate the results of the latest research into vehicle operating costs carried out by TRRL in the Caribbean. Resulting from this study new relationships have been developed for predicting vehicle speed and fuel consumption, spare parts consumption, maintenance labour, tyre wear and vehicle depreciation.

As further results become available from other studies, these will also be incorporated into the model.

3. THE NEW MODEL

3.1 General

A detailed flow diagram of the model is shown in Figure 3. Operation of the model starts by defining the road alignment. Construction details are then input and the cost of construction determined. Alternatively the construction cost is specified directly. For each year that the road is open to traffic, road deterioration, road user costs and road maintenance costs are predicted. Road deterioration is calculated as a function of the construction specification, the maintenance policy, the rainfall and the traffic. A vehicle performance submodel uses details of the road geometry and the road surface condition to predict the vehicles' speeds and fuel consumptions. Costs of fuel, oil, tyres, vehicle maintenance, depreciation, etc, are then determined to give the total vehicle operating costs for the year. An option is available to calculate time costs and these are based on the values of time which must be input to the model. Road maintenance requirements are found from the condition of the road surface in
conjunction with the maintenance policy, and these are used to find the maintenance cost. The model then continues with its year-by-year analysis. The process continues for the selected analysis period and, at the end, the total construction costs, road maintenance costs and road user costs will be known. These costs can then be discounted at different discount rates.

An analysis period of up to 50 years can be considered and this may include up to four years for the initial construction to take place.

3.2 Traffic

The model can consider separately up to seven types of vehicle defined in four classes: passenger cars, light commercial vehicles, buses and heavy commercial vehicles. Input is required on vehicle price and tyre price for all classes and vehicle load and equivalence factors for the heavy vehicles. The loads and equivalence factors can be different for vehicles moving in opposite directions.

Traffic growth forecasts must be made for each vehicle type and these forecasts can be specified in a variety of ways to allow any type of growth function to be simulated. The model uses relationships for vehicle speeds which were developed under 'free-flow' conditions and hence it cannot predict the speed reductions caused by traffic congestion.

3.3 Road design

The geometry of the road is defined by its horizontal and vertical alignments and its cross-section.

The horizontal alignment is specified in terms of the average degree of curvature per kilometre; this is used only in the prediction of vehicle speed. The vertical alignment is specified in terms of the rise and fall and is used in the prediction of vehicle speed and fuel consumption and also in the prediction of the loss of material from gravel roads. The road cross-section is defined in terms of carriageway and shoulder width and this affects vehicle speed, rate of road deterioration and road maintenance costs.

If the model is used to determine construction costs, then more detailed information about the vertical alignment and the cross-section must be input.

3.4 Construction cost

On many occasions that the model is used, the construction cost will already be known or an existing road will be under examination. However, the model can be used to estimate the earthworks, site clearance and pavement costs for roads at the feasibility study stage of design, and this is described in detail in Appendix 1.

3.5 Road deterioration

Roads will deteriorate at different rates depending on whether they are earth, gravel or paved. The deterioration relationships used in the model were developed during the Kenya study and are given in Appendix 2.

Earth and gravel road deterioration is defined in terms of roughness, rutting and looseness of the surface material, which are all functions of the traffic volume and the type of surface material. Additionally,
for gravel roads, deterioration is also expressed in terms of gravel loss, which is a function of traffic volume, rainfall and the gradient of the road. Four different types of gravel surface are considered by the model.

Paved road deterioration is defined as a function of roughness and cracking. These are functions of the pavement strengths (modified structural number) and the cumulative axle loading expressed in terms of equivalent standard axles.

The model predicts deterioration of the road surface in each year that the road is trafficked.

3.6 Road user costs

Road user costs are determined for each year that the road is open to traffic and consist of time costs and vehicle operating costs. Vehicle costs are determined from relationships developed in Kenya\textsuperscript{3} and the Caribbean\textsuperscript{9,10}, and are given in Appendix 3. Time costs are found from the product of the value of passengers' time, which may be input to the model, and journey time which is found from the road length and the average vehicle speeds.

Vehicle speed is calculated separately for each type of vehicle and for each direction of travel. Speeds are used in conjunction with details of the road geometry and surface characteristics and details of the vehicle to predict fuel consumptions. Fuel costs are found from this and the prices of petrol and diesel oil. The consumption of lubricating oil is built into the model for different types of vehicle running on paved and unpaved roads. The cost per journey is found from this and the unit cost of the oil. The cost of replacement parts for a journey over the road is related to the new vehicle price, the distance travelled by the vehicle since new and the roughness of the road surface. Tyre costs are related to the roughness of the road and, for heavy vehicles only, to the gross vehicle weight. Depreciation of vehicles has been related to the vehicle's age in years. An initial age spectrum of vehicles may be input and this may be modified, if required, each year by vehicle growth and wastage. In addition, the model calculates crew costs and standing costs, all of which are related to journeys over the road being studied.

To calculate these costs, the model requires input on fuel and lubricant prices, tyre costs, new vehicle prices, crew hourly rates, and the value of passengers' time.

3.7 Road maintenance costs

Maintenance of paved roads is assumed to consist of patching, surface dressing and overlaying. For unpaved roads, maintenance is assumed to consist of grading, and regravelling of gravel roads. The model computes the cost of carrying out the maintenance that has been specified by the user. A cost of maintenance overheads which should include shoulder maintenance and ditch clearing may also be included if required.

A description of the road maintenance routine is given in Appendix 4.

3.8 Stage construction

As part of the maintenance routines it is possible to study the effects of planned improvements to the standard of the surface of the road. Earth roads can be gravelled, gravel roads paved and paved roads overlaid. Any number of additional layers can be added but the alignment and width of the road will remain unchanged. After an upgrading, the maintenance policy may also change.
Stage construction which involves changing the geometry of the road can only be studied by making separate runs of the model.

3.9 Costing

All calculations within the model are carried out on a quantity or non-dimensional basis and input unit rates are used to determine costs. Thus the model can be used with any system of costs or prices and its relationships do not become outdated because of the effects of inflation or changing relativities in commodity prices.

Prices should be expressed in either market or economic terms depending on the type of analysis being carried out.

An important aspect of the cost of building roads in developing countries is the foreign exchange requirement. The model has the facility to calculate the foreign exchange requirements for construction, road maintenance and vehicle operation based on percentages of components such as fuel, construction plant and materials, etc, which must be bought with foreign exchange.

3.10 Computer requirements and availability

The computer program (RTIM2) and user manual will be made available through:

Highway Engineering Computer Branch
Department of Transport
St Christopher House
Southwark Street
London SE1 0TE
United Kingdom

The program is written in Standard FORTRAN and consists of 6,000 statements. The total size of the program is 130k bytes. On the ICL 4/70 computer the program has a system overhead of approximately 29k giving a total program size of 159k bytes. This can be reduced in size by using a simple overlay structure which would result in a total program size of approximately 92k.

The program requires input in card image form and a separate input device may be used for input of the ground data. Three sequential files are required for use as backing store and these may be magnetic tapes or disk files. The program prints output to a lineprinter.

The run time of the program on the ICL 4/70 is of the order of only a few seconds.

4. SUMMARY

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. An attempt has been made to obtain a better understanding of the interaction between road construction and maintenance standards and the cost of operating vehicles in order to improve the quality of decisions made at the planning stage of road investment projects. The relationships derived from various studies have been built into a computer model which may be used to aid investment decisions within the roads sector in developing countries.
The relationships in the model allow it to be used to study the interrelationships between road design and construction standards, road maintenance policy, vehicle characteristics, traffic flow and growth rate, environment and road deterioration. The model can be used to study many aspects of a road investment project such as the optimum maintenance standards for the road, the choice of an earth, gravel or bituminous pavement, and the benefits of adopting any number of different stage construction options. The model will also allow the planner to study the consequences of uncertainties in traffic forecasts or in the discount rate.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


7. APPENDIX 1
CONSTRUCTION COSTS

7.1 Introduction

Normally, the cost of construction of the road will be input directly to the model by the user. However, if this cost is not known, the costs of earthworks, site clearance, pavement, shoulders and other costs can be computed by RTIM2 in the following way.

7.2 Alignment

The horizontal alignment is specified as an average degree of curvature per kilometre, ie the total number of degrees through which the horizontal alignment of the road turns divided by the alignment length in kilometres.

The vertical alignment used by the model is defined by an intersection point chainage and level and a curve length for each vertical curve. This alignment may be specified in this form directly. Alternatively, the radius of vertical curvature may be specified instead of curve length in which case curve length is calculated from

\[ c_i = \left| \frac{r_i (g_i - g_{i+1})}{g_i - g_{i+1}} \right| \]

where \( r_i \) is the radius of curvature and \( g_i \) is given by

\[ g_i = \frac{q_i - q_{i-1}}{p_i - p_{i-1}} \]

where \( p_i \) and \( q_i \) are the chainage and level of the intersection point \( i \).

A suitable vertical alignment may be generated automatically from details of the ground longitudinal section using program VENUS311.

7.3 Input of construction data

The earthworks model works from ground cross-sections specified by chainage, centre line level and crossfall. The cross-sections may be specified directly in this form or may be given in the form of offsets and levels at intervals of chainage in which case the centre line level and crossfall are calculated from

\[ z_i = \frac{d_{1i} h_{2i} - d_{2i} h_{1i}}{d_{1i} - d_{2i}} \]

and

\[ \tan \alpha_i = \frac{h_{1i} - z_i}{d_{1i}} \]
where $z_i$ is the centre line level, $\tan \alpha_i$ the crossfall, $h_{1i}$ the ground level at offset $d_{1i}$ and $h_{2i}$ the ground level at offset $d_{2i}$. The ground must be defined at the start and finish points of the road (the first and last intersection points); any cross-sections lying outside are ignored.

Road cross-section details are shown in Figure 4. Slopes are specified as run/rise but are inverted by the model which uses tangents. If slopes are not specified, cut slopes, fill slopes and ditch side slopes are assumed to be 1 in 1 and ditch bottoms are assumed to be flat.

Characteristics of the soil are specified in terms of the percentage of it which, on average, will be unsuitable for use as fill. The factors by which the material will bulk after excavation and compact again may also be specified but these are both taken as unity if the user does not give any other value. The CBR of the soil when the pavement has been constructed must also be given.

Cost of earthworks are specified in terms of cost of excavation and loading, spreading and compaction, haulage, borrowing and spoiling. These are expressed as a unit cost per cubic metre for each except haulage which is cost per cubic metre-kilometre hauled.

A maximum ground crossfall may be specified above which a retaining wall will be used when the road is on fill. Dimensions of the retaining wall may be specified as in Figure 5 where

\[
\begin{align*}
    a &= \text{width of the top of the wall} \\
    1 \text{ in } b &= \text{batter of the wall} \\
    c &= \text{depth to the foundation} \\
    d &= \text{thickness of the foundation} \\
    h &= \text{height of wall as determined by the model.}
\end{align*}
\]

The construction cost for retaining walls is specified as a cost per unit volume.

Up to five different types of vegetation cover are allowed, each with its own cost of clearing. The type of vegetation cover may be specified on each ground cross-section. A depth of topsoil may be specified as in Figure 4 and this is removed on a cost per unit volume basis before other earthworks quantities are determined.

Three different types of pavement are allowed: earth, gravel and paved. For earth roads, only a soil code and description are required. Gravel and paved roads may have any number of layers. For each layer, the following information is required: layer thickness, material type code and layer strength. Costs for each layer may be specified as a cost per square metre or a cost per cubic metre, or a combination of both.

Drainage, structures and miscellaneous items are specified as fixed costs and overheads are specified as a percentage of all other costs.

### 7.4 Costing of earthworks and retaining walls

Earthworks and retaining wall costs are calculated in the following way.

Each cross-section on the ground model is considered in turn. The road level at the centre line is calculated from the formula
\[ z_i = q_j + g_j (x_i - p_j) + \left( \frac{g_{j+1} - g_j}{2c_j} \right) (x_i - p_j + q_j/2)^2 \]

if the cross-section lies on a vertical curve, or from

\[ z_i = q_j + g_j (x_i - p_j) \]

where

\[ g_j = \frac{q_j - q_{j-1}}{p_j - p_{j-1}} \]

and \( z_i \) is the road centre line level at chainage \( x_i \), \( p_j \) and \( q_j \) are the current intersection point chainage and level respectively and \( c_j \) is the length of the vertical curve. The road level at the edge of the right hand and left hand shoulders is then calculated from

\[ t_o = z_i - \frac{1}{2} wc sc - ws ss \]

where \( wc \) is the width of the whole carriageway, \( sc \) the crossfall of the carriageway and \( ws \) and \( ss \) are the shoulder width and crossfall respectively.

The ground level at the right hand shoulder is calculated from

\[ t_1 = z_i + \tan \alpha (\frac{1}{2} wc + sc) \]

where \( \alpha \) is the ground crossfall. The level of the road is compared with the level of the ground after removal of topsoil at the right hand shoulder to determine whether it is in cut or fill. A full cut cross-section is shown in Figure 6 and a full fill section in Figure 7. The area of a full cut or full fill cross-section is found by summing the trapezoidal and triangular areas shown in Figures 6 and 7, working from the right hand shoulder to the right hand toe and then back across the road to the left hand toe making allowances for the depth of pavement and shoulders and depth of topsoil. The area of a trapezoidal section (Figure 8) is calculated from

\[ a = \frac{1}{2} (t_1 - t_2 + t_3 - t_4) \]

and the area of a triangular section (Figure 9) is calculated from

\[ a = \frac{(t_1 - t_2)^2}{2(\tan \beta - \tan \alpha)} \]

with notation as given in the Figures.

On a cross-section in which the ground line intersects the formation level (Figure 10), areas of both cut and fill will be present on the cross-section. These areas are summed separately and the areas on the transitional segment itself (Figure 11) are calculated from
\[ a_1 = \frac{t(t_2-t_1)^2}{2(t_2-t_1 + t_3-t_4)} \]

and

\[ a_2 = \frac{t(t_3-t_4)^2}{2(t_2-t_1 + t_3-t_4)} \]

with notation as in Figure 11.

If the ground crossfall exceeds the value specified in the input and the road is on fill, a retaining wall is provided as in Figure 5. Values of a, b, c and d are provided by the user and the wall height, h, is determined by the model from the height of s the shoulder above the ground level. No fill slope is provided when a retaining wall is used. The area of the wall at each cross-section is determined from

\[ A_x = w.d + h(w + h/2b) \]

where \( w = (a.b + d)/b \)

and other notation is as given in Figure 5. The volume of retaining walls between cross-sections is found from

\[ v_w = (h_1 + h_2) \frac{a_x}{2} \cdot x \]

where \( h_1 \) and \( h_2 \) are the retaining wall heights at the two cross-sections and \( x \) is the distance between the cross-sections. Volumes are calculated separately for left and right hand sides of the road.

The volumes of cut and fill between each pair of cross-sections are calculated in the following way. If both cross-sections contain cut (Figure 12), the cut volume is given by

\[ v_c = \frac{(a_{c1} + a_{c2})}{2} \cdot x \]

where \( a_{c1} \) and \( a_{c2} \) are the areas of cut on the two cross-sections and \( x \) is the distance between the cross-sections. Similarly, if both cross-sections contain fill (Figure 12) the fill volume is given by

\[ v_f = \frac{(a_{f1} + a_{f2})}{2} \cdot x \]

where \( a_{f1} \) and \( a_{f2} \) are the two cross-sectional fill areas. If the section is a fill-cut transition (Figure 13) the volumes are given by

\[ v_f = a_{f1} \cdot t/2 \]

where

\[ t = \frac{a_{f1} \cdot x}{a_{f1} + a_{c2}} \]

13
and \( v_c = a_{c2} (x-t)/2 \)

Alternatively, if the section is a cut-fill transition (Figure 14), the volumes are given by

\[
v_c = a_{c1}.t/2
\]

where \( t = \frac{a_{c1}.x}{a_{c1} + a_{f2}} \)

and \( v_f = a_{f2} (x-t)/2 \)

A mass-haul diagram is set up by considering the relationship between accumulated earthworks balance against chainage. At any chainage, the accumulated earthworks balance is given by

\[
b_i = b_{i-1} + \frac{v_s - v_f}{f_b.f_c}
\]

where \( b_i \) is the accumulated balance at cross-section \( i \), \( v_s \) is the suitable cut volume and \( v_f \) the fill volume between cross-sections \((i-1)\) and \( i \), \( f_b \) is the bulking factor and \( f_c \) the compaction factor. A typical mass-haul diagram is shown in Figure 15.

The marginal haul is calculated from

\[
M = \frac{\text{unit cost of borrow} + \text{unit cost of spoil}}{\text{unit cost of haulage}} . 1000 \text{ metres}
\]

If no haul cost has been specified, the marginal haul is set to a distance which is greater than the total length of the road.

Each station on the diagram is tested in turn to determine whether a balance line should pass through it. This is done by searching ahead of the station of interest to find the next station at which the accumulated earthworks balance is the same; this may or may not lie on a cross-section. The actual chainage of the end of the balance line is calculated from (Figure 16)

\[
x_b = \frac{(x_k - x_{k-1}) \lvert b_{k-1} - b_b \rvert}{\lvert b_k - b_{k-1} \rvert} + x_{k-1}
\]

where \( b_b \) is the ordinate of the balance line and \( x_k \) is the chainage and \( b_k \) the ordinate at cross-section \( k \).

If the length of this balance line is less than the marginal haul, a balance line is set up and the area of the balance loop is calculated from the triangular and trapezoidal areas shown in Figure 17. The triangular area at the start of the balance loop is calculated from

\[
\text{area} = \frac{1}{2} \lvert b_{j+1} - b_b \rvert (x_{j+1} - x_b)
\]
where \((x_{bl}, b_{bl})\) is the start of the balance line and \((x_{j+1}, b_{j+1})\) is the location of the first point on the mass-haul diagram after the start of the balance line. Each of the trapezoidal areas is calculated from

\[
\text{area} = \frac{1}{2} (|b_{i-1} - b_{bl}| + |b_i - b_{bl}|)(x_i - x_{i-1})
\]

where \(b_{bl}\) is the ordinate of the balance line and \((x_i, b_i)\) is a point on the mass-haul diagram. The triangular area at the end of the balance loop is calculated from

\[
\text{area} = \frac{1}{2} |b_{k-1} - b_{bl}| (x_{b2} - x_{k-1})
\]

where \((x_{b2}, b_{b})\) is the end of the balance line and \((x_{k-1}, b_{k-1})\) is the last point on the mass-haul diagram before the end of the balance line. Finally, the area of this balance loop is added to that of any previous loops and the point that ended this balance line is taken as the first point of the next potential balance line.

If the length of the balance line is greater than the marginal haul, it will not be economical to haul material. The search for a new balance loop must start again at the cross-section following that which started the discarded loop and the volume of material between this cross-section and the previous one must be imported or exported as appropriate.

When the end of the alignment has been reached, the total area of balance loop is multiplied by the bulking factor to give the product of the volume of material and the distance hauled. The volume of spoil calculated in the mass-haul routine is added to the volume of compulsory spoil (the difference in the cut volume and the suitable cut volume) to give the total volume of spoil. The costs of excavation, compaction, haulage, borrow, spoil and retaining walls are found by multiplying the quantity which has been derived above by the respective unit cost. These are added to give the total cost of earthworks and retaining walls.

Foreign exchange costs are calculated where appropriate by multiplying the quantities derived by the specified foreign exchange percentage.

7.5 Site clearance, pavement and other costs

The type of ground cover for site clearance is specified at each ground cross-section along the road. The total length of road for each type of ground cover is found by summing, at each cross-section, the chainage length between the current cross-section and the previous cross-section for the site clearance type specified. The area to be cleared for each site clearance type is determined from the product of the total road length for the site clearance type and the clearing width. The cost of clearing each type of ground cover is calculated from the following

\[
\text{cost}_i = a_i c_i
\]

where \(a_i\) is the area to be cleared in hectares and \(c_i\) is the unit cost of clearing this type of vegetation. Foreign exchange costs are calculated if required by finding the product of the actual cost and the foreign exchange percentage. The total cost of site clearance is found by adding the costs of clearing individual vegetation types.

No pavement or shoulder costs are calculated if the road is an earth road because it is assumed that traffic will drive directly on the formation which is constructed by earthmoving. A gravel or paved road
may consist of several pavement and shoulder layers. These are numbered from the bottom. The area of the carriageway is calculated from the product of its length and its width. The volume of material in each pavement layer is calculated from

\[ V_{ci} = a_c t_i \]

where \( a_c \) is the carriageway area and \( t_i \) is the thickness of layer \( i \). The materials cost for each layer is calculated from the product of the volume \( V_{ci} \) and the unit cost per cubic metre of the material. The cost of laying this material is calculated from the product of the carriageway area \( a_c \) and the unit cost per square metre of laying. The materials cost and the laying cost are added to give the total cost for each layer. Foreign exchange costs, if required, are calculated in the same way as for earthworks and site clearance. The cost of each layer is calculated in this way and then these are added to give the total cost of the pavement. The cost of shoulders is calculated in exactly the same way as that of the pavement.

Fixed and miscellaneous costs which are specified are added directly to the construction cost total. Foreign exchange costs are calculated if required. The percentage of the construction cost which will be paid in overheads and supervision is determined and added to the construction cost to give the total cost of construction. The percentages of the construction cost and foreign exchange component that will be spent in each of the four years allowed for construction are then determined.
8. APPENDIX 2
ROAD DETERIORATION

8.1 Paved roads

Deterioration of paved roads is predicted in terms of changes in roughness (riding quality) and cracking. First, a modified structural number is determined to give an index of pavement strength.

Modified structural number is given by

\[ SN_1 = \sum_{i=1}^{n} a_i D_i + 3.51 \log_{10} CBR - 0.85 (\log_{10} CBR)^2 - 1.43 \]

where

- \( a_i \) = the strength coefficient of layer \( i \)
- \( D_i \) = the thickness of layer \( i \) in inches
- \( CBR \) = the California Bearing Ratio of the subgrade.

Where for bituminous surfacings

\[ a_i = AASHO \text{ strength coefficient} \]

for road bases (see Figure 18)

\[ a_i = (29.14 \ CBR_i - 0.1977 (CBR_i)^2 + 0.00045 (CBR_i)^3) \times 10^{-4} \]

and for sub-bases (see Figure 19)

\[ a_i = 0.01 + 0.065 \log_{10} (CBR_i) \]

where \( CBR_i \) = the California Bearing Ratio of the layer \( i \).

The modified structural number after overlay is given by

\[ SN^1 = f \cdot SN^1_o + a_k D_k \]

where

- \( SN^1_o \) = the modified structural number of the existing pavement when constructed
- \( a_k \) = the strength coefficient of the overlay
- \( D_k \) = the thickness of the overlay in inches
- \( f \) = factor by which the modified structural number of the existing pavement has been reduced at the time of the overlay (specified by the user).

For paved roads, the total number of standard axles which have passed over the road since construction or overlay is determined. The traffic loading in the heaviest traffic lane is used. Average deterioration during the year is determined after the passage of half the current year's standard axles.
Roughness is predicted from (see Figure 20)\(^{12}\)

\[ R = R_0 + mN \]

where \( N \) = the number of millions of standard axles which have passed over the road

\( R_0 \) = the initial roughness of the road

and \( m = \frac{1250}{\text{antilog}_{10}(a^{1/3} - b^{1/3} - 1.3841)} \)

where

\( a = \sqrt{0.20209 + 23.1318c^2} - 4.8096c \)

\( b = \sqrt{0.20209 + 23.1318c^2} + 4.8096c \)

and \( c = 2.1989 - SN^1 \).

Cracking is predicted together with patching on the assumption that all areas where cracking exceeds 5 m/m\(^2\) are patched to sub-base level (see Figure 21)\(^{12}\)

\[ C + P = 300 \left[ \frac{SN^1 - 4 + \frac{72N_1}{(SN^1)SN^1}}{SN^1} \right], \quad \text{SN}^1 < 4.0, \quad C + P \geq 0 \]

\[ C + P = \frac{21600N_1}{(SN^1)SN^1}, \quad \text{SN}^1 \geq 4.0, \quad C + P \geq 0 \]

where

\( C + P = \) the patching in m\(^2\)/km for each traffic lane

\( N_1 = \) cumulative traffic in millions of equivalent standard axles since last resurfacing.

### 8.2 Unpaved roads

For unpaved roads, the number of vehicles in each class are added together to give the total daily traffic. The number of gradings in each season is specified by the user. The numbers of vehicles between gradings in each season is found by apportioning the total annual traffic by the length of each season and the number of gradings. The average condition of both the wet and dry seasons is used to predict vehicle operating costs and the worst condition is used to predict maintenance requirements.

Roughness is given by (see Figures 22 and 23)\(^4\)

\[ R = 3250 + 1255T \]

for 'sand' earth roads

\[ R = 3250 + 314T \]

for 'clay' earth roads

\[ R = 3250 + 84T - 1.62T^2 + 0.016T^3 \]

for lateritic, quartzitic and volcanic gravel roads

\[ R = 6500 + 58T - 1.0T^2 + 0.017T^3 \]

for coral gravel roads

where \( T \) is the traffic since grading in thousands of vehicle passes.
Rut depth is given by (see Figures 24 and 25)\(^4\)

\[ R_D = 14 + 1.2T \]

for earth roads

\[ R_D = 11 + 0.23T - 0.0037T^2 + 0.000073T^3 \]

for lateritic gravel roads

\[ R_D = 17.5 + 0.73T \]

for volcanic, quartzitic and coral gravel roads

where \( T \) is as above.

Looseness is given by (see Figure 26)\(^4\)

\[ L_D = 1.0 \]

for lateritic and coral gravels in the wet season

\[ L_D = 1.5 + 5e^{0.35T} \]

for earth roads and quartzitic and volcanic gravels in the wet season

\[ L_D = 1.5 + 14e^{0.23T} \]

for all roads in the dry season

where \( T \) is as above.

Annual gravel loss is given by (see Figure 27)\(^4\)

\[ G = F(4.2 + 0.092T_A + 3.5 R^2_A + 1.88 V_c) \left[ \frac{T_A^2}{T_A^2 + 50} \right] \]

where

- \( T_A = \) total annual traffic in both directions measured in thousands of vehicles
- \( R_f = \) annual rainfall in metres
- \( V_c = \) average percentage road gradient
- \( F = \)
  - 1.5 for coral gravels
  - 0.94 for lateritic gravels
  - 1.1 for quartzitic gravels
  - 0.70 for volcanic gravels.

Gravel loss is measured in mm.

When the residual thickness of the gravel layer falls below 5 mm the road is considered by the model to be an earth road.
9. APPENDIX 3
ROAD USER COSTS

9.1 Vehicle age spectrum

The age spectrum for each type of vehicle in the first year of trafficking may be input by the user; alternatively, an age spectrum is assumed by the model to be of the form:

\[ v_i^o = v_o [1 - \frac{i}{Y}], \quad i \leq Y \]
\[ v_i^o = 0, \quad i > Y \]

where \( v_i^o \) = the number of vehicles of age \( i \) in the first year
\( v_o \) = the number of new vehicles in the first year
\( Y \) = 10 for cars and light vehicles
\( = 12 \) for buses and trucks
\( v_o \) = \( \frac{2N}{Y+1} \)

where \( N \) = total number of vehicles in this class in the first year.

The user must decide whether this age spectrum remains constant throughout the analysis period or whether it is modified from year to year to reflect the wastage and scrapping of old vehicles and the introduction of new vehicles. In the latter case, the percentage of vehicles of age \( y_i \) that remain in use is given by (see Figure 28):

Passenger cars and light commercial vehicles:
\[ w_1 (i) = 100 \cos^2 (5.74 i/180) \]

Buses:
\[ w_2 (i) = 100 \cos^2 (5.19 i/180) \]

Heavy commercial vehicles:
\[ w_3 (i) = 100 \cos^2 (5.32 i/180) \]

where \( w \) is the percentage of vehicles which were new in any year which are still in use \( i \) years later.

For each vehicle class, the number of vehicles \( i \) years old running on the road in year \( y \) is given by:

\[ v_i^y = v_i^{y-1} \frac{w(i)}{w(i-1)} \]

where \( v_i^y \) is the number of vehicles of age \( i \) in use in year \( y \)
\( w \) is the appropriate function \( w_1, w_2 \) or \( w_3 \) from above.

The total number of vehicles which are at least one year old are found from the above and this figure is subtracted from the number of vehicles actually on the road to give the total number of new vehicles, thus modifying the age spectrum for the current year.
9.2 Speed and time

Vehicle speeds are calculated separately for different directions and for each half per cent increment in road gradient. On unpaved roads, speeds are also calculated separately in the wet and dry seasons.

The following variables are used:

- $S_C =$ observed ‘free-speed’ of passengers cars in km/h
- $S_L =$ observed ‘free-speed’ of light vehicles in km/h
- $S_T =$ observed ‘free-speed’ of trucks in km/h
- $R =$ rise in m/km
- $F =$ fall in m/km
- $C =$ curvature in degrees/km
- $R =$ roughness in mm/km
- $M =$ moisture content as a percentage
- $RD =$ rut depth in mm
- $PW =$ power to weight ratio in brake horsepower/tonne
- $W =$ road width in metres
- $\Delta V =$ reduction in speed in km/h when the road is less than 5.0 metres wide
- $V =$ speed in km/h.

9.2.1 Cars.

Paved roads

$$V = S_C + (0.483 - 0.00833S_C)RS + (-0.025 - 0.00050S_C)F + (0.115 - 0.00220S_C)C - 0.00087R$$

For roads < 5.0 metres wide, $\Delta V = -8.1 (5.0-W)$

Unpaved roads

$$V = S_C + (0.272 - 0.00573S_C)RS + (-0.021 - 0.00058S_C)F + (0.122 - 0.00285S_C)C - 0.00089R - 0.13M - 0.19RD$$

For roads < 5.0 metres wide, $\Delta V = -8.1 (5.0-W)$

9.2.2 Light vehicles.

Paved roads

$$V = S_L + (0.763 - 0.01359S_L)RS + (-0.082 + 0.00036S_L)F + (0.087 - 0.00185S_L)C - 0.00066R$$

For roads < 5.0 metres wide, $\Delta V = -7.0 (5.0-W)$

Unpaved roads

$$V = S_L + (0.369 - 0.00845S_L)RS + (-0.088 + 0.00036S_L)F + (0.064 - 0.00198S_L)C - 0.00095R - 0.29M - 0.20RD$$

For roads < 5.0 metres wide, $\Delta V = -7.0 (5.0-W)$

9.2.3 Buses and trucks.

Paved roads

$$V = 49.0 + (1.429 - 0.02860S_T)RS + (-0.867 + 0.01318S_T)F + (0.177 - 0.00346S_T)C + (-1.900 + 0.04346S_T)PW - 0.00106R$$

For roads < 5.0 metres wide, $\Delta V = -6.2 (5.0-W)$
Unpaved roads
\[ V = 45.0 + (0.363 - 0.01149 S_T)RS + (-0.055 + 0.00086S_T)F + (0.061 - 0.00176S_T)C 
+ (-2.396 + 0.05401S_T)PW - 0.00060R - 0.22M - 0.27RD \]

For roads < 5.0 metres wide, \( \Delta V = -6.2 \, (5.0-W) \)

9.2.4 Passenger time. Vehicle speeds are used to calculate journey times and these may be used in conjunction with input values of passengers' time to determine time costs. Time costs are output separately for normal and for generated traffic.

9.3 Fuel

Fuel consumption is calculated for each half per cent increment in road gradient and for the two directions of traffic in order to provide the mean value for each class of vehicle.

The following variables are used:

- \( V \) = speed in km/h
- \( RS \) = rise in m/km
- \( F \) = fall in m/km
- \( GVW \) = gross vehicle weight in tonnes
- \( FL \) = fuel consumption in millilitres/km.

9.3.1 Cars.

\[ FL = \left(24 + \frac{969}{V} + 0.0076V^2 + 1.33RS - 0.63F + 0.0029F^2\right) \times 1.08 \]

\[ FL \geq 5.0 \]

9.3.2 Light vehicles.

\[ FL = \left(72 + \frac{949}{V} + 0.0048V^2 + 1.118 (GVW \times RS) - 1.18F + 0.0057F^2\right) \times 1.08 \]

\[ FL \geq 5.0 \]

9.3.3 Buses and trucks.

\[ FL = \left(29 + \frac{2219}{V} + 0.0203V^2 + 0.848 (GVW \times RS) - 2.6F + 0.0132F^2\right) \times 1.13 \]

\[ FL \geq 5.0 \]

9.4 Lubricating oil

<table>
<thead>
<tr>
<th></th>
<th>cars</th>
<th>light vehicles</th>
<th>heavy vehicles</th>
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<tr>
<td>Paved roads</td>
<td>1.2</td>
<td>1.8</td>
<td>4.0</td>
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<tr>
<td>Unpaved roads</td>
<td>2.4</td>
<td>3.6</td>
<td>8.0</td>
</tr>
</tbody>
</table>
9.5 Tyres

The following variables are used:

\[ R = \text{roughness in mm/km} \]
\[ T = \text{tyres consumed per km.} \]
\[ \text{GVW} = \text{gross vehicle weight in tonnes} \]

9.5.1 Cars and light vehicles.

Paved and unpaved roads (Figure 29)

\[ T = \left( \frac{0.0927 + 0.6275e^z}{1 + e^z} \right) \times 10^{-3}; \quad z = -3.753 + 0.000695R \]

9.5.2 Buses and trucks.

Paved roads (Figure 30)

\[ T = \left( \frac{0.1054 + 0.1921e^z}{1 + e^z} \right) \times \text{GVW} \times 10^{-4}; \quad z = -4.302 + 0.000737R \]

Unpaved roads (Figure 30)

\[ T = \left( \frac{0.1054 + 0.1838e^z}{1 + e^z} \right) \times \text{GVW} \times 10^{-4}; \quad z = -4.254 + 0.000770R \]

9.6 Spare parts

The following variables are used:

\[ K = \text{total kilometres run to date (this is determined from the product of the average annual kilometres run and the average age of vehicle which is, in turn, found from the vehicle age spectrum)} \]
\[ R = \text{roughness in mm/km} \]
\[ VP = \text{price of an equivalent new vehicle} \]
\[ PC = \text{spare parts cost per km.} \]

9.6.1 Cars and light vehicles.

Paved roads (Figure 31)

\[ PC = \left( \frac{1.57 + 18.08e^z}{1 + e^z} \right) \times K \times 10^{-11} \times VP; \quad z = -4.673 + 0.000812R \]

Unpaved roads (Figure 31)

\[ PC = \left( \frac{1.57 + 14.17e^z}{1 + e^z} \right) \times K \times 10^{-11} \times VP; \quad z = -4.018 + 0.000725R \]
9.6.2 Buses.
Paved and unpaved roads (Figure 32)
\[ PC = \left( \frac{0.40 + 4.73e^Z}{1 + e^Z} \right) \times K \times 10^{-9} \times VP; \quad z = -5.076 + 0.001051R \]

9.6.3 Trucks.
Paved roads (Figure 33)
\[ PC = \left( \frac{1.22 + 6.00e^Z}{1 + e^Z} \right) \times K \times 10^{-11} \times VP; \quad z = -4.879 + 0.000984R \]

Unpaved roads (Figure 33)
\[ PC = \left( \frac{1.22 + 3.81e^Z}{1 + e^Z} \right) \times K \times 10^{-11} \times VP; \quad z = -4.173 + 0.000747R \]

9.7 Maintenance labour hours
The following variables are used:--

PC = spare parts cost per km
R = roughness in mm/km
VP = price of an equivalent new vehicle
LH = hours of maintenance labour per km

9.7.1 Cars and light vehicles.
Paved and unpaved roads (Figure 34)
\[ LH = \left[ \frac{695 + 383e^Z}{1 + e^Z} \right] \times \frac{PC}{VP}; \quad z = -6.373 + 0.00159R \]

9.7.2 Buses.
Paved and unpaved roads (Figure 34)
\[ LH = \left[ \frac{2484 + 2172e^Z}{1 + e^Z} \right] \times \frac{PC}{VP}; \quad z = -6.373 + 0.00159R \]

9.7.3 Trucks.
Paved and unpaved roads (Figure 34)
\[ LH = \left[ \frac{2819 + 2507e^Z}{1 + e^Z} \right] \times \frac{PC}{VP}; \quad z = -6.373 + 0.00159R \]
9.8 Depreciation

Depreciation costs (Figures 35 and 36) are determined for those vehicles running on the road during the current year and also for those vehicles which have been scrapped since the previous year. In the latter case, the vehicles are assumed to depreciate from their last value to zero.

9.8.1 Scrapped vehicles. The number of vehicles which are scrapped at the end of year \( y \) is the difference between the number running in the previous year \( (y-1) \) of age \( i-1 \) and the number running in year \( y \) of age \( i \).

\[
\Delta v^y_{i} = v^y_{i-1} \left[ 1 - \frac{w(i)}{w(i-1)} \right]
\]

9.8.2 Cars and light vehicles. Depreciation is given by:

\[
D_y = 0.22 v^y_1 + 0.1406 v^y_2 + \sum_{i=3}^{8} 0.078 v^y_i + 0.0714 v^y_9 \\
+ 0.78 \Delta v^y_1 + \sum_{i=2}^{8} (0.6394 - 0.078 (i-2)) \Delta v^y_i \\
+ 0.1 \sum_{i=9}^{13} \Delta v^y_i
\]

9.8.3 Buses and trucks. Depreciation is given by:

\[
D_y = 0.1083 v^y_1 + \sum_{i=2}^{10} 0.6615 \left( i^{1/3} - (i-1)^{1/3} \right) v^y_1 + 0.0281 v^y_1 \\
+ 0.8917 \Delta v^y_1 + \sum_{i=2}^{10} (1.5532 - 0.6615 i^{1/3}) \Delta v^y_i \\
+ \sum_{i=11}^{13} 0.1 \Delta v^y_i
\]

9.9 Crew hours

The cost of crew hours per kilometre is determined from the ratio of annual crew hours to annual kilometres run.

9.10 Standing charges

Standing charges and overheads may have both a fixed and a variable component. The fixed cost per kilometre is added to the vehicle running cost before the percentage component is derived.

9.11 Costing

All costs of vehicle operation and time are derived on a per-kilometre basis. Costs are derived by multiplying the estimates of quantities by unit rates. Vehicle operating costs are accumulated separately from time costs, and both are determined separately for normal and for generated traffic. In addition, any foreign exchange costs may be determined and tabulated.
10. APPENDIX 4
ROAD MAINTENANCE COSTS

10.1 Types of maintenance

Maintenance is defined as routine, recurrent or periodic\(^\text{13}\). Routine maintenance activities are those that are required whether the road is paved or unpaved and do not depend on traffic level. They consist of items such as grass cutting, drain clearing, re-cutting ditches and maintenance of culverts, bridges and road furniture. They are represented in the model by an input fixed cost.

Recurrent maintenance requirements depend on traffic level and consist of patching for paved roads and grading for unpaved roads.

Periodic maintenance consists of those traffic-dependent activities which are needed at intervals of greater than one year. For paved roads, periodic maintenance consists of surface dressing and overlaying. For unpaved roads, periodic maintenance consists of regravelling.

Depending on the road type being studied, recurrent maintenance policies are input to the model along with trigger values for determining when to carry out periodic maintenance. After periodic maintenance has been carried out, a new recurrent maintenance policy may be introduced and this will stay in force until the trigger for the next periodic maintenance activity has been reached. As many maintenance policies as are required may be specified, but they must be planned to take account of predicted traffic growth and available resources.

10.2 Recurrent maintenance

10.2.1 Paved roads. For paved roads, recurrent maintenance consists of patching cracks and potholes. It is assumed that all areas where cracking exceeds 5 m/m\(^2\) are patched to sub-base level according to the relationship in Section 8.1 (Figure 21). Patching is costed on a cubic metre basis.

It is not possible to use the model to study the consequences of not patching or of reducing the amount of patching below that given above.

10.2.2 Unpaved roads. Recurrent maintenance of both gravel and earth roads consists of grading. The number of times that the road is graded in both the wet season and the dry season must be input and the cost of this is specified on a per-kilometre basis. The frequency of grading can be changed after a regravelling operation.

10.3 Periodic maintenance

10.3.1 Paved roads. Periodic maintenance of paved roads may consist either of surface dressing or of overlaying. Surface dressing can be triggered by specifying a time interval in years and an overlay can be triggered by specifying the traffic loading in terms of cumulative standard axles since new construction or last overlay. The trigger value for either operation must be input.
In the case of overlay, the user may specify a percentage value for the loss of strength of the pavement since newly constructed or since an overlay was laid. The roughness of the road will be reduced by an overlay to a value input by the user. The roughness of the road is unchanged, however, by the application of a surface dressing.

The description and costing of added layers for surface dressing and overlay is similar to that for new pavement construction.

10.3.2 Unpaved roads. Earth and gravel roads may be regravelled as a periodic maintenance policy. The type of gravel may be different to the present type of material or, in the case of earth roads, gravel may be placed where none was there previously.

Regravelling is triggered either by a time interval in years or by a limiting residual thickness of gravel, whichever is reached the sooner. The new roughness immediately after the regravelling must be input by the user.

Costing for regravelling is similar to that for placing gravel during construction.

10.4 Upgrading

Periodic maintenance may be used to upgrade the quality of the pavement provided that the road width or alignment do not change.

An earth road may be upgraded to a gravel road by regravelling as described above. A gravel road may be upgraded to a paved road by adding extra pavement layers. In this case, it is assumed that any residual gravel is graded off before the new pavement is constructed. A paved road can be strengthened by applying an overlay. These facilities allow the model to be used to study the economics of stage construction on the same alignment.

10.5 Shoulder maintenance

Routine maintenance of shoulders should be included as one of the fixed cost items. Recurrent grading of unpaved shoulders should be included as part of the unit price for grading. Recurrent patching of paved shoulders and the repair of edge damage should be included as a fixed cost. Periodic maintenance and upgrading of shoulders can be included as part of the periodic maintenance input.

10.6 Costing

All maintenance requirements are estimated by the model on a quantity basis, and costs are found by applying input unit prices to these. Overheads may be included as both a fixed cost and as a percentage of the other maintenance costs, both for recurrent and periodic maintenance. Foreign exchange costs may also be derived and these are tabulated separately.
Fig. 1 Interrelationships between factors affecting vehicle operating costs

Fig. 2 Outline flow-diagram of the TRRL Road Investment Model
Fig. 3 Detailed flow-diagram of TRRL Road Investment Model
Shoulder width

Carriageway width

Pavement depth

Shoulder depth

Carriageway crossfall

Depth of topsoil

Fill slope

Ground crossfall

Shoulder crossfall

Ditch depth

Ditch side slope

Cut slope

Ditch bottom slope

Ditch bottom width

Fig. 4 Road cross-section

Slope = \( \frac{1}{b} \)

Fig. 5 Retaining wall dimensions
Fig. 6 Trapezoidal and triangular areas making up a full cut cross-section

Fig. 7 Trapezoidal and triangular areas making up a full fill cross-section
Fig. 8 Typical trapezoidal segment of cross-sectional area

Area = \frac{1}{2} (t_1 - t_2 + t_3 - t_4)

Fig. 9 Typical triangular segment of cross-sectional area

Area = \frac{1}{2} (t_1 - t_2)

\[ t = \frac{t_1 - t_2}{\tan \beta - \tan \alpha} \]
Area $a_1 = \frac{t(t_2-t_1)^2}{2(t_2-t_1+t_3-t_4)}$

Area $a_2 = \frac{t(t_3-t_4)^2}{2(t_2-t_1+t_3-t_4)}$

Fig. 10 Typical transitional cross-section area

Fig. 11 Typical transitional segment of cross-sectional area
Fig. 12 Road section with both cut and fill volumes

Fig. 13 Road section with fill-cut transition

Fig. 14 Road section with cut-fill transition
Accumulated earthworks balance (cut-fill)

![Diagram of mass-haul diagram](image)

**Fig. 15** Mass-haul diagram

Accumulated earthworks balance (cut-fill) (b)

![Diagram showing part of mass-haul diagram](image)

**Fig. 16** Part of mass-haul diagram showing balance line ending between cross-sections
Fig. 17 Part of mass-haul diagram showing balance loop comprising triangular and trapezoidal areas
Fig. 18 Strength coefficients for granular bases

\[ a_2 = (29.14 \text{ CBR} - 0.1977 \text{ (CBR)}^2 + 0.00045 \text{ (CBR)}^3) \times 10^{-4} \]

Fig. 19 Strength coefficients for sub-base materials

\[ a_3 = 0.01 + 0.065 \log_{10}(\text{CBR}) \]
Fig. 20 Roughness relationships

Fig. 21 Cracking and patching relationships
Fig. 22 Roughness versus traffic for earth roads

Fig. 23 Roughness versus traffic for gravel roads
Fig. 24 Rut depth versus traffic for earth roads

\[ RD = 14 + 1.2T \]

Fig. 25 Rut depth versus traffic for gravel roads

Other gravels
\[ RD = 17.5 + 0.73T \]

Lateritic gravel
\[ RD = 11 + 0.23T - 0.0037T^2 + 0.000073T^3 \]
Fig. 26 Looseness versus traffic for unpaved roads

Fig. 27 Gravel loss versus traffic
Fig. 28 Vehicle wastage relationships

- **BUSES**
  \[ W = 100 \cos^2 \left( 5.19 \frac{\pi}{180} \right) \]

- **TRUCKS**
  \[ W = 100 \cos^2 \left( 5.32 \frac{\pi}{180} \right) \]

- **CARS AND LIGHTS**
  \[ W = 100 \cos^2 \left( 5.74 \frac{\pi}{180} \right) \]
Fig. 29 Tyre consumption equation for cars and light vehicles

Fig. 30 Tyre consumption equations for trucks and buses
Fig. 31 Parts consumption equations for cars and light vehicles

Fig. 32 Parts consumption equation for buses
Fig. 33 Parts consumption equations for trucks

Fig. 34 Maintenance labour relationships
**Fig. 35** Car and light vehicle depreciation

**Fig. 36** Bus and truck depreciation
The TRRL road investment model for developing countries (RTIM2): LINDA L PARSLEY and R ROBINSON: Department of the Environment Department of Transport, TRRL Laboratory Report 1057: Crowthorne, 1982 (Transport and Road Research Laboratory).

A computer model is described which is designed to aid investment decisions within the roads sector in developing countries.

The model calculates the construction cost of a road and predicts the condition of the road as time passes and vehicles travel over it. Having predicted the condition of the road, the model estimates the costs of road maintenance and the cost of operation of the vehicles for each year. All these costs are then discounted back to the base year and summed over the life of the road to obtain the total cost. All estimates are made in terms of physical quantities and costs are obtained by applying unit rates to these quantities.

The results of a study in Kenya were used to calibrate a prototype version of the model. This prototype was tested extensively for the appraisal of road projects in developing countries. As a result of this experience, the model has now been reprogrammed to make it easier to use and to fit onto smaller computers. The opportunity has also been taken to include in the model the results of the latest research in developing countries in this field carried out by TRRL.

The relationships built into the model allow it to be used to study the interrelationships between road design and construction standard, road maintenance policy, vehicle characteristics, traffic flow and growth rates, environment, and road deterioration. The model can be used to study various aspects of a road investment project such as the optimum maintenance standards for the road, the effects of providing an earth, gravel or bituminous pavement, or the differing benefits that can be obtained by adopting various stage construction options. The model will also allow the planner to study the consequences of uncertainties in traffic forecasts or in the discount rate.

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