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Highway Design Study Phase I: The Model

January, 1971

The Highway Design Study focuses on the interrelationships among construction costs, road maintenance costs and vehicle operating costs with the objective to improve the basis for decisions on design standards of low volume roads. Phase I of the study, which is reported on herein, provides a methodological framework which delineates the underlying engineering relationships in a prototype simulation model. Phase II of the study, currently underway in East and West Africa, will focus on empirical estimation of certain of the most critical of these relationships and seeks particularly to collect accurate and comprehensive data on vehicle operating costs under conditions typical to developing countries.

The Highway Design Model incorporates three functional submodels: construction, roadway maintenance, and vehicle operation. Each submodel estimates resources consumption first and calculates the money cost of those resources using prices separately specified. Hence, the model is adaptable to any economy regardless of relative costs of different resources. Construction costs are estimated for specified design standards in a given environment using productivities of equipment packages. The maintenance submodel predicts the deterioration of the roadway surface as a function of the original construction standards, the specified maintenance policy, and traffic volume. Vehicle operating costs are then predicted as a function of the roadway condition and the vehicle characteristics. Thus the model can be used to examine the tradeoffs among construction standards, maintenance standards, and vehicle operating costs.

A summary of the report precedes the Table of Contents. This highly detailed model is operational on an experimental basis and for those interested in applying it a User's Manual is available. Anyone wishing additional information may contact Mr. Jan de Weille (X3687) or Mr. Clell Harral (X2756).

Sector and Projects Studies Division

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Preface

This is the final report of a Highway Design Study project conducted by CLM Systems, Inc. for the International Bank for Reconstruction and Development. The purpose of the project as stated in the contract is as follows:

"to take the first step toward providing a satisfactory decision-making framework with which to tackle the question of the optimum design standards of low traffic volume roads in less developed countries.

The decision criterion will be: minimization of total transport costs (road construction, road maintenance, and vehicle operating costs).

This investigation should enable the Bank to define a possible second phase of the study aimed at further development and improvement of the decision-making framework and its data base."

Due to the limited available resources, the study was not expected to produce a fully operational and comprehensive model. It was initially anticipated that the "first step towards providing a satisfactory decision-making framework" would consist of the development of a small prototype computer based model which "covers the essential aspects of the problem in a conceptually sound way and will serve as a basis for further development".

Although the model actually developed goes beyond the prototype stage and it may, under special circumstances, be used in the preliminary design of a highway, it should be considered an experimental model. Substantial additional work is required to develop it into a production type model.

Once the model is fully operational, the Bank may use it in the planning and preliminary design of rural roads that carry a low volume of traffic. In this application it can be used to explore construction, maintenance, and vehicle operating cost tradeoffs for a specific location and time period. Through sensitivity analysis the model may be used to explore probable impacts of changes in demand levels, capital costs, and other factors not under the planners control. The model may also be used in a more general context to evaluate policies related to maintenance expenditures, construction staging, and design standards.
This report discusses the development of that experimental model and its rationale. After discussing the basic framework of the model, the structure of its three major submodels are discussed, and the results of a limited sensitivity analysis are presented. Recommendations for future work are contained in the final section of the report.

The authors wish to thank Messrs. K.W. Guenther, L.A. McCoomb, M. A. Becker, P. Messeri and M.J. Markow for their invaluable assistance in developing the highway cost model and in preparation of this report. We thank Messrs. J. de Weille and C. Harral of the World Bank for their assistance and support throughout the project. Also, we thank those who reviewed and commented on the literature reviews and earlier drafts of this report—Mr. A.A. Duncan of the World Bank, Messrs. Bonney, Hide, and Hodges of Road Research Laboratory, Professor Betts of Arizona State University, Mr. P. Leger of Laboratoire Central des Ponts et Chaussees.
Summary

Phase I of the Highway Design Study resulted in a prototype or experimental highway cost simulation model. The model consists of three functional submodels, a construction cost submodel, a roadway maintenance submodel, and a vehicle operating cost submodel. These submodels are used to simulate each year of roadway life. An overall accounting and control routine records total discounted costs and controls the flow of data between submodels. Each submodel estimates resource consumption first and estimates the money value of those resources using prices supplied by the analyst. Hence, the model is adaptable to any economy regardless of relative costs of different resources.

The construction cost submodel is used for each year in which construction or reconstruction occurs. The model estimates the amount of required earthwork using either a one point digital terrain model or a non-linear function of contours crossed. Drainage structure requirements are estimated using empirical relationships derived by Lago and McCoomb. The resource requirements for earthwork, drainage structures, clearing, and surfacing are then estimated using productivities of equipment packages provided by the analyst. Unit prices convert these resource requirements to a cost.

The maintenance submodel predicts the deterioration of the roadway surface as a function of the specified maintenance policy, the original construction specifications, the rainfall, and previous traffic. It also estimates the resources required to implement the analyst specified maintenance policy and, using analyst specified prices, determines the cost of those resources.

The vehicle cost submodel predicts average vehicle velocity as a function of the vehicle specifications and the deteriorated roadway. After average velocity is estimated fuel consumption, tire wear, maintenance, and depreciation are computed. Then unit prices are used to compute the perceived user cost. The perceived user cost and a demand schedule are used to estimate average daily traffic for the year. Unit opportunity costs are then used to estimate the total vehicle operating cost for the year.

Maintenance cost estimation, and vehicle operating cost estimation, are repeated for each year in the analysis period. Construction cost estimation is done for each year in which construction or reconstruction occurs. The entire process
may then be repeated for alternative designs, traffic volumes, etc., to search for the design and maintenance policy which is preferred.

By repeating the steps of estimating construction, maintenance, and user costs, the model simulates the interaction between construction, maintenance, and use of the road. Instead of making independent estimates of construction, maintenance, and user costs for the analysis period, each of the submodels takes advantage of previous predictions of the other two. Thus the cost estimates are based on a simulation which includes some of the feedback characteristics of the actual system.

The model is built up from many detailed engineering relationships so that it will have a sound causal structure. This approach was necessary in order that the cost differences predicted by the model would be appropriately sensitive to alternative designs, construction procedures, and maintenance policies. The resultant model, built up from many engineering relationships, may produce biased estimates of total cost in any given situation but the bias should be consistent for the alternatives being compared. This is due to the impossibility of completely describing every road and associated vehicles and maintenance in terms of a general mathematical model.

Hence, the model should only be used by experienced engineers and then only on an experimental basis. In any specific situation, recalibration to local conditions will be necessary. However, if this is done by knowledgeable engineers, the model can then be used to evaluate an extremely wide range of alternative designs and maintenance policies. It can facilitate a systematic search over alternatives which would be impossible with conventional manual procedures for cost estimation.

The model is a prototype experimental model. It is intended to lead towards a model which can be used routinely in planning and preliminary design. The present prototype model has been tested with the limited data available during this study. These tests demonstrate the feasibility of developing a highway cost model which will be useful in planning and design. The cost estimates responded realistically to variations of design variables. The sensitivity runs also demonstrated that the accuracy of the cost estimates is very dependent on some relationships which at present have very little data to support them. This is especially true of the effect of surface roughness on vehicle costs and on the effects of construction and maintenance practices upon surface roughness. Consequently, it is recommended that field work
be conducted to improve the accuracy of the estimates of key
parameters in the model. It is also recommended that the
model be used by experienced engineers in the planning and
design of one or two World Bank projects so that the strengths
and weaknesses of the model can be identified more clearly.
Both steps should be completed before attempting to develop
a production model for routine use by planners and designers.
Chapter 1. Introduction

To help achieve efficient highway transportation, analytical models should be available to assess accurately and quickly the contributions of each component of the highway system cost. The approach should consider the vehicle operating cost and the maintenance cost of the facility as well as its initial construction cost. The model should be capable of estimating the cost of each of these components and provide for the evaluation of the tradeoffs which exist amongst them. These tradeoffs involve issues of timing and the opportunity costs of deferring expenditures. The model should be applicable in any country. To fully understand the highway design tradeoffs, generalized staging models are inadequate and models of the physical system are required. No single model of the system which would be satisfactory for design purposes now exists. However, there are a number of models which relate vehicle costs to surface type (2), rise and fall (5), etc. There are also models which can be used to estimate earthwork volumes and drainage structure requirements(4,7). There are some fairly comprehensive models, such as the one by Lago (3), and some more specific, such as Soberman's (6).

Unfortunately, these models do not form a comprehensive whole. They are fragmented views of a large complex problem. They frequently use data measured in varying levels of accuracy and with different surrogates. To aid people who plan highway investments in developing countries these works are brought together in a decision-making framework in this study.

It should be recognized that the primary objective of this study has been the development of a satisfactory decision-making framework rather than a fully operational model for the optimum design of low volume roads in the developing countries. Therefore, the model described in this report and the results presented should be viewed as experimental and output of the model should not be used for actual design work except in special circumstances. To develop the model into a fully operational one for use as a production model requires substantial additional work in terms of system debugging, model calibration, and model application to several actual ongoing design projects under supervision of model analysts and design engineers.
An Overview of the Model

Road transportation will be viewed as a production process. In this process, a time stream of inputs (construction, maintenance, and vehicle operating resources) are transformed in a time stream of outputs (transportation services). As in most production processes, the inputs can be combined in many ways. The design problem is finding that combination of inputs which over time results in the most efficient production process. In terms of transportation for developing countries, this may imply time staging of investments—the upgrading or rebuilding of roads as traffic volume increases. Viewed in this context, the roadway design problem can be seen as a problem of selecting the optimal amount, mix, and timing of capital inputs.

The desired model will be a quick, easy to use cost estimator. It is intended that it be used by the highway planner who seeks to identify the optimal combination and timing of transport inputs. The ultimate model will be used to explore design and maintenance tradeoffs for low volume rural roads in developing countries throughout the world. Total project costs over the analysis horizon will be estimated as a function of the following types of input:

- a. the demand for transportation
- b. unit price of inputs
- c. the social opportunity cost of capital
- d. the physical environment (terrain, climate, geology, available construction materials)
- e. engineering decisions (alignment, profile, pavement specifications)
- f. maintenance policy.

The model presented in this paper is a prototype which has the desired characteristics of the ultimate model. It requires the same types of input to compute total project cost over the analysis horizon. It is sensitive to the same design and maintenance type parameters. It can be used in its current form to explore construction and maintenance tradeoffs.

 Desired Characteristics: Because the model will be used at several stages during the preliminary analysis of a project, it is designed to be responsive to different levels of information. For example, during initial analysis the terrain is described by the rise and fall of the ground along the path of the road. Later, when a specific alignment is investigated, the model can accept more.
detailed digital terrain information. Similarly, the model is able to analyze roadway operating costs for either specific vehicles or for representative vehicles.

Another desirable characteristic of the model is that it incorporates the best available information relating highway transport costs to highway design and maintenance standards. The form of the model is not constrained by the form of a particular optimization technique. Rather, the model is designed as an iterative time simulation of construction, maintenance, and operations activities. This iterative simulation permits the most flexible approach to representing important physical and economic relationships.

The iterative simulation approach also facilitated the development of a highly modular model. The modularity of the model makes it relatively simple to incorporate new information as it becomes available. For example, as better information on the relationship between vehicle maintenance requirements and roadway surface roughness is developed, it can be incorporated without altering other parts of the model.

Simulation Framework: The model simulates construction, maintenance, and operations activities for each year in the analysis horizon of a road project. This is shown schematically in Figure 1.1. Input to the model is a description of environment, the projected traffic flow and projected construction and maintenance actions or standards over the analysis horizon. This input is used to simulate individual resource consuming activities, such as construction of a road segment, patching of pavement, or operation of a vehicle. Output from the model is a discounted total cost for the planning horizon plus several subdivisions of that cost. In particular, costs are shown for each year and a breakdown by labor, materials, transport, and equipment is presented. In addition, some detailed output on physical quantities is available.

The entire analysis period is divided into years. Each year is divided into seasons or subperiods to reflect different rainfall and traffic conditions. Their length is specified by the user. For each year in the analysis horizon resource consuming activities are simulated and costs computed. These costs are output and also discounted and added to the discounted total cost. Maintenance operations occur in all years except construction years. The amount of maintenance depends on the seasons or subperiod within the year. Construction occurs in the first year and reconstruction occurs in any year specified by the user.
Design and Cost Input:
  a. Analysis Horizon
  b. Traffic Profile
  c. Environment
  d. Design and Maintenance Standards
  e. Unit Costs, including the Discount Rate

Is period a construction period?
  If yes, call construction cost submodel
  If no, continue.

Call maintenance cost submodel.

Call vehicle operating cost submodel.

Print Report

Last period? No

Yes
Stop
Traffic volumes in each year are influenced by the condition of the road in that year. The condition of the road depends in part on the traffic volume in the previous year. Hence, the model simulates construction, then maintenance, and finally vehicle operations for each year. It is assumed that construction and reconstruction occur instantaneously at the beginning of the year and do not increase vehicle operating costs.

**Resources Consumed**

Although the model is called a highway cost model, the basic strategy is to first predict consumption of resources in physical units and then to multiply those by appropriate unit costs. This strategy is adopted so the model can be applied in countries where factor prices differ widely. Hence, it is necessary to identify the individual resources being consumed. As the first part of the cost prediction process, we start by dividing the total system cost into construction costs, maintenance costs, and vehicle operation costs. Within each of these categories, subcategories of cost can be identified that are predictable using relationships available in the literature.

**Construction Resources** - The construction costs may be separated into six categories:

1. Earthwork Costs
2. Pavement or Surfacing Costs
3. Site Preparation
4. Drainage
5. Overhead and Supervision
6. Other

Of these six categories, earthwork costs and pavement or surface cost are the most important for most roadways. Hence, they have received the most attention in the design of the construction costs submodel. The quantity of earthwork required is predicted using one of two types of terrain models depending upon the data available to the analyst. The cost of pavement or surfacing is determined by specifying a particular pavement design. The cost of site preparation is based on a cost per unit area; and drainage cost is estimated using the Lago (3) model in association with data developed by McCoomb (4).

**Maintenance Resources** - The maintenance cost is estimated using Alexander's model (8). It is divided into four principal categories:

1. Surface Maintenance
2. Shoulder Maintenance
3. Drainage Maintenance
4. Vegetation Control
Surface maintenance includes all activities associated with both paved and unpaved surfaces such as patching and sealing paved surfaces, blading unpaved surfaces, and adding gravel or crushed stone to gravel roads. Drainage activities include the clearing of side ditches, and the cleaning and repair of culverts and small bridges. The principal difficulties in the maintenance model are predicting the rate of deterioration of the roadway and estimating the quality of the roadway after maintenance action. Research results available for estimating the rates of deterioration of paved surfaces come principally from the AASHO Road Test (1). Engineering judgement and general information in the literature are used to predict the quality of unpaved surfaces as a result of deterioration and maintenance actions.

**Operating Resources** - Operating costs in the model may be divided into three categories:

1. Costs Associated with the Journey Time (Driver Wages, Vehicle Interest, etc.)
2. Fuel Costs
3. Cost of Vehicle Wear (Maintenance, Depreciation, and Tire Wear)

The journey time cost prediction is based upon several relationships any one of which could be the limiting factor for journey time, depending on the particular conditions of the roadway and vehicle. Fuel costs are estimated using the Saal (5) model with modifications to allow for surface type or from an equation based on horsepower used to climb a continuous grade. Vehicle wear and tire wear costs are based on de Weille's tables (2). In addition, the model could be modified to incorporate costs for enroute delays and the cost of accidents. However, at this time there are no satisfactory models relating these costs to characteristics of the roadway.

**Tradeoff Factors**

Tradeoffs between operating costs and construction costs relate principally to the roadway alignment, profile, and surface type. In general, more earthwork is required for a more level profile or straighter alignment. Level profile or straight alignment reduces the journey time, fuel requirement, and the vehicle wear. In addition, operating costs are reduced by using better surfacing materials, because rolling resistance is reduced.

The principal tradeoff between operation and maintenance costs is related to surface characteristics. Well-maintained roads will permit vehicles to achieve the same speed on older roads as was possible when they were new. As the surface deteriorates,
the increased roughness necessitates slower operating speeds and increased vehicle wear.

The basic tradeoff between construction and maintenance is that a stronger pavement will deteriorate less rapidly for any given vehicle load, and hence, will require less frequent maintenance to retain the same pavement quality.

Plan of the Report

The following three chapters of the report describe in detail the three major sections of the highway cost model— the construction submodel, the maintenance submodel, and the operations submodel. The next chapter, Chapter 5, describes an example analysis which was performed to evaluate the model and demonstrate its applicability to the problems of planning low cost rural roads. Chapter 6 contains the conclusions of this research and the recommendations for future work.
REFERENCES


Chapter 2. Construction Submodel

Introduction

The construction submodel has been designed to satisfy a number of basic objectives:

- Handle a variety of conditions in different contexts associated with the design and construction of low design standard roadways including staged construction and reconstruction of paved and unpaved roadways under various economic and technological conditions.
- Produce material, equipment, labor and transport resource estimates for each of the primary construction operations.
- Accept as input varying types, quantities, and qualities of data on which to base fundamental design decisions.
- Permit the investigation of many types of design and operation tradeoffs including analysis of individual operations and technologies.

Model Overview

The construction submodel which satisfies the above objectives lies between the traditional detailed highway design procedures and the simpler total cost models more common to transport planning studies (Figure 2.1). Detailed design procedures and computer models provide accurate results but are generally too expensive and time-consuming to use in the context of a larger and more complete model. Total cost models are typically simple, easily programmed, and inexpensive to use. Unfortunately, the accuracy and sensitivity of this form of model is not sufficient to satisfy the objectives of an overall highway cost model. Physical quantities are neither directly calculated nor estimated in these models and the cost data on which the model is based are seldom transferable from one region to another.

The construction submodel which has been developed is a compromise that yields estimates of acceptable accuracy without undue cost or complexity. A key word is "estimated" which may differ from detailed engineering design where physical quantities are generally "calculated." Wherever possible, the model utilizes estimating procedures in place of direct calculation techniques.

The basic operation of the submodel is the estimation and summation of physical quantities for the earthwork, pavement, drainage, and site preparation operations. Construction productivities in terms of units/hour of equipment packages are applied to determine the time of each operation, and equipment and labor rates in dollars/hour are applied to determine equipment and labor costs. Where appropriate, transport
Figure 2.1. Accuracy vs. Cost of Model
distances and costs can be specified so that transport requirements can be estimated. Individual quantities can be multiplied by appropriate unit costs to estimate the source acquisition cost of the required materials. Provision is also made for structural and other miscellaneous cost items and for such general costs as administration, supervision, and overhead. A macro flow chart of the construction submodel is shown in Figure 2.2.

A large number of construction related studies have been performed and many total and partial models have been developed. This past work is, in general, good and many studies have made one or more significant contributions. No single existing model, however, completely satisfied the objectives of the construction submodel. The literature survey indicated though that individual components could be taken from several existing models and put together in a new model which would more nearly achieve the submodel objectives. The models and submodels that were found to be most useful were in general those that were natural outgrowths or extensions of existing design procedures. The emphasis of this phase of the study was not to develop and calibrate advanced new techniques but to integrate and to make better use of already existing methods.

The construction model can be executed in one of three modes:

- New construction
- Pavement upgrading
- Roadbed reconstruction.

Most existing construction models, and indeed most construction related data, are oriented to new construction. Reconstruction, upgrading, and construction staging are rarely treated. Yet, many of the Bank's problems are reconstruction or upgrading projects. A feasible design alternative which should be evaluated for new roads is to construct the facility in stages, matching the increase in traffic volumes with corresponding increases in road quality. Separate productivities and costs can be specified for reconstruction operations since the nature of the required construction operations is generally different than for new construction and the technology available may be different than that utilized in the original construction.

Primary Submodel Assumptions

Four major assumptions governed the development of the construction submodel. They were as follows:

1. Horizontal alignment is specified.
2. Topographic data are available in the form of either contour maps or aerial photographs.
3. Major structures are to be treated independently.
4. Specific design standards and construction technologies should not be built into the model.
Figure 2.2. Construction Submodel -
Macro Logic

INITIALIZATION

ESTIMATE SITE PREPARATION QUANTITIES AND COST

ESTIMATE EARTHWORK QUANTITIES AND COST

ESTIMATE ROADWAY AND SHOULDER PAVEMENT QUANTITIES AND COST

ESTIMATE DRAINAGE REQUIREMENTS AND COST

SUM COMPONENT COSTS TO DETERMINE TOTAL COST

ESTIMATE OVERHEAD AND "OTHER" COST COMPONENTS
The specification of an alignment implies that alternative locations can be handled by re-running the model for each separate alignment.

The scale of available mapping has been found to be widely variable. It is assumed that in general only relatively gross maps, e.g., 1:24,000, are available or possibly only aerial photographs from which ground profiles can be produced. To match this varying data availability, two different forms of terrain data can be accepted. Minimal soil mapping forms or knowledge is also assumed to be available so that construction materials can be located.

Major structures for river crossings and other large obstacles are not explicitly accounted for but culverts and structures for minor stream crossings and other cross drainage purposes are included. An allowance for major structures, however, can be included.

Cost models can incorporate engineering design procedures to automatically design one or more roadway components. The most frequently found example is pavement design where the required thicknesses of the individual pavement layers are automatically selected to satisfy a pre-determined design standard. A model whose primary objective is the selection of design standards should not itself incorporate existing standards. For example, pavement design including material layer types and thicknesses are specified as part of the basic model input data. Variables such as road life then, in principle, can be interpreted from data generated by the model, and are not exogeneously specified.

Model Input

The construction submodel is designed to operate with the varying amounts and types of data that may be available. Data will differ from study to study and additional data will be collected as a study progresses. Data requirements of the models are therefore flexible, not fixed and rigid.

Detailed and complete input data requirements are described with the instructions for using the model. The following is a summary of the information that is needed by the construction submodel:

- Alignment length.

- Profile geometry in terms of either a maximum grade, if exact geometry is not known, or a series of elevations and stations along a specific vertical profile.

- Roadway description consisting of widths and cross-slopes for the roadway, shoulders, and ditches; cut and fill side slopes.

- Pavement design consisting of a basic pavement type, the number of material layers in the roadway and shoulder, and the thickness and type of each material layer.
- Site clearing width.

- Topographic description in terms of either a measure of the terrain rise and fall or a one-point terrain model. Terrain rise and fall is measured by the number of contour lines crossed in a unit length. The one-point terrain model is described by sequentially specifying a series of stations and ground elevations along the alignment.

- Reconstruction schedule consisting of the time each reconstruction or upgrading is to occur and the type of reconstruction that is to be performed.

- Soil and ground cover or vegetation data.

- Drainage and hydrology data.

- Transport haul: distances for the borrow material, pavement quantities, and cross-drainage structures.

- Construction technology data for the major construction operations including productivities of labor-equipment packages, labor hourly rates, equipment hourly rates, transport unit costs, and material acquisition costs.

Model Output

While the primary output data of the construction submodel are total costs, detailed or unaggregated cost and quantity data calculated by the model are also available. Where the model is being used primarily as a design aid by an engineer, it is this more detailed information that will be most useful.

Cost data are output after each new or reconstruction calculation and include in addition to a total cost, cumulative and incremental costs in actual and discounted terms for material, equipment, labor, and transport components.

The following detailed output data are optionally available:

- Site preparation: area in hectares to be cleared; and time, labor cost, and total cost of the site preparation operation.

- Earthwork: cut, fill, and borrow quantities; borrow and transport cost; and time, labor cost, equipment cost, and total cost of the earthmoving operation.

- Pavement: for each defined roadway and shoulder pavement layer; surface area, volume, source cost of the material, transport cost, time required to place the particular material layer, labor cost, equipment cost, and total layer cost.
- Drainage; total required length of each of five possible culvert sizes, source acquisition cost, transport cost, and total drainage cost.

- Other miscellaneous cost components such as structures, overhead, move-in, supervision, etc., separated into labor and equipment components.

**Earthwork**

Construction of the basic roadbed generally constitutes the largest single cost component in the development of a low design standard road. Earthwork costs are also among the more difficult to estimate because of their dependence on topography, geology, climate, site access, and basic road design.

A wide variety of earthwork estimating techniques exist and considerable development has gone into computer aided roadway design systems. These systems, however, tend to be of high accuracy, have relatively high input data requirements, and require either a medium or large sized computer. The criteria for the Highway Cost Model tend to the opposite extremes: a lower level of accuracy and one that is compatible with the other component submodels, low input data requirements, and small size so that the model can be implemented on a small computer.

Terrain descriptors range from quantitative and complete digital terrain models to qualitative and approximate classification and evaluation schemes. The descriptor chosen falls between these two extremes and takes the form of a flexible "one point" numeric terrain model that can be measured as a series of either stations and elevations along the roadway alignment or contour line densities representing the rate of rise and fall of the topography. The "one point" terrain model was chosen because it yields satisfactory earthwork estimates for planning purposes under a variety of conditions and because it facilitated development of a prototype model. Extensions to include three point elevation, cross-slope or other more elaborate and accurate terrain models are easily achievable given the highly modular model structure. These extensions would be desirable if the earthwork estimate and roadway design results were to be used in making final location and design related decisions.

The general logic of the earthwork submodel is shown in Figure 2.3. Earthwork quantities are estimated on the basis of the input roadway design and topography data. The amount of borrow necessary is then calculated. Given these two figures, offsite transport requirements and placement costs can be estimated and a total earthwork cost can be determined. Internal haulage is taken into account through choice of an earthwork productivity.
Figure 2.3

EARTHWORK SUBMODEL

INPUT

Road Design:
- Alignment length (m)
- Roadway Cross-Section (m)
- Profile (m)
- Pavement Thickness (m)

State of Nature
- Topography

Transport Factors
- Borrow Source Cost ($/m³)
- Transport Cost ($/Km/m³)
- Haul Distance (m)

Technology Data
- Productivity Rate (m³/Hr)
- Labor Rate ($/Hr)
- Equipment Rate ($/Hr)

MODEL

Quantities (m³) = f (topography, alignment, profile, cross-section, pavement)

Borrow (m³) = Embankment Quantity (m³)

- Excavation Quantity (m³)

OUTPUT

Borrow Cost = Source Cost x Borrow
T Cost = Borrow x Cost x Distance

Time = Quantity/Productivity
L Cost = Time x Labor
E Cost = Time x Equip.

Total Earthwork Cost
TC = L Cost + E Cost + T Cost + Borrow Cost
Two separate methods are provided to estimate the actual earthwork quantities. The first method utilizes terrain data in the form of stations and elevations, designs an approximate roadway cross-section at each defined terrain point along the alignment, estimates the volume of cut and fill between successive pairs of terrain stations, and sums these incremental volumes to determine a total volume. Profile geometry in terms of VPI stations and elevations are required for this method of earthwork estimation. The second method of estimating earthwork quantities is more approximate and utilizes terrain information described by contour line densities and a profile described by its maximum profile grade. Quantities are estimated on the basis of unit quantity curves relating volume to contour line density for various profile grades. These curves were derived by conducting a series of controlled experiments on a computer using a roadway design system.

The earthwork model estimate, as described, assumes a single material; it does not classify excavation requirements into earth, rock, unsuitable, and other possible categories. An extension to the current model to account for rock classification has been developed and furnished to the sponsor as a separate document. Other highway design systems are available that are capable of handling the full classification of material quantities, as well as incorporating more accurate terrain descriptors. One such system is ICES ROADS developed by the M.I.T. Department of Civil Engineering (5).

One Point Earthwork Model

Earthwork volumes based on the one point station-elevation terrain model are computed by the average end area method where the end areas are a function of the height of fill or depth of cut and the dimensions of the roadway cross-section. The profile grade definition is defined on a simplified VPI to VPI basis without the inclusion of vertical curve considerations. A station and elevation is defined for each VPI.

The depth of pavement is taken into consideration in determining the amount of fill and cut required. For fill sections, the pavement layers reduce the amount of earth needed to bring the alignment to grade while for cut sections, the excavation requirement is increased to accommodate the pavement structure within the profile grade constraint.

If both the back and the ahead end areas are either all cut or all fill, then the two end areas are simply averaged and the averaged end area is multiplied by the distance between the two stations to determine the incremental volume. If the end areas are of an opposite type, then the road transitions between cut and fill. In this case, the station of the transition point (zero depth of cut) is estimated via linear interpolation and the segment is divided into cut and fill portions. The end areas at a terrain station are determined by summing the trapezoidal sections across the roadway template. A single section may involve both cut and fill if the level ground line passes below the roadway.
crown elevation but above the ditch elevation. In this case, the points where the roadway cross-section transitions from fill to cut are determined and the end areas calculated accordingly. Experience in using one point terrain models has shown that this approach can provide satisfactory accuracy for purposes of planning and preliminary design. Detailed logic and computational equations for this earthwork submodel are described in the program documentation.

**Contour Line Density Earthwork Model**

The second method of estimating earthwork quantities is based on data and techniques generated by Augusto L. Soux of the Systems Group of TRW, Inc., under contract C-353-66 (Neg.) for the Office of High Speed Ground Transportation, United States Department of Transportation (4). The model estimates the volume of earthwork required to bring a roadway alignment to grade as a function of the maximum allowable grade, road width, side slope, and the density of ten foot elevation contours per mile.

The data base was generated using a simple one point terrain model and utilized 84 separate roadway designs through a wide spectrum of terrain types. Road profiles were fitted to these terrain profiles and adjusted by trial and error to yield a minimum earthwork design, while at the same time retaining a balance of cut and fill. The earthwork volumes were computed based on a simple trapezoidal prism formula:

\[ Q = d(bh + zh^2) \]

where

- \( Q \) = earthwork volume
- \( b \) = road width
- \( z \) = road side slope

and where "h" is the difference between the elevation of the terrain and the road profile at each station.

The earthwork volumes, computed in the above manner, were then plotted against contour density, that is, the number of 10-feet contours traversed per mile for the particular alignment in question. Curves were then fitted to these data points, one for each maximum allowable grade, to permit interpolation of the earthwork volumes for all combinations of contour density and maximum grade intermediate to the data points (Figure 2.4).

To expand the model to permit any combination of road width and road side slope, earthwork volume versus contour density curves were split into two component curves, \( Q_b \) and \( Q_z \), equivalent to the road
Figure 2-4

Earthwork Quantities

Vs.

Number of 10' Contour Lines Crossed for
Minimum Allowable Radius of
Vertical Curvature of 0.006

b = 50 ft.

reproduced from [4]
width factor \( (h) \) and the side slope factor \( (h^2) \) in the \( Q \) formula. This reduces the quadratic formula to \( Q = d(bQ + zQ) \), where \( Q \), \( d \), \( b \), and \( z \) are as previously defined, and \( Q_b \) and \( Q_z \) are graphical functions of the maximum allowable grade and contour density.

The computer subroutine developed utilizes one set of the \( Q_b \), \( Q_z \) curves and automates the earthwork estimation procedure by interpolating the appropriate values of \( Q_b \) and \( Q_z \) and then substituting these in the \( Q \) formula.

Since the \( Q_b \) and \( Q_z \) curves are non-linear, it was necessary to approximate each by a series of linear segments of the form \( Q_b = A_{ij} + B_{ij}X \), and \( Q_z = C_{ij} + D_{ij}X \) (Figure 2.5). The corresponding intercepts \( A_{ij} \), \( C_{ij} \); slopes \( B_{ij} \), \( D_{ij} \); and ranges of \( X \) (the contour density) \( L_{ij} \), \( L_{ij} \) for each of these segments were measured and entered into a matrix form where the rows represent the particular curve (maximum allowable grade) and the columns represent the linear segments (range of contour density). For example, the matrix element \( A_{23} \) would be the intercept of the 1% \( b \) curve (row 2) for a linear segment having a range from 14.5 to 25 ten foot contours per mile. Since the original curves are logarithmic, the log of each intercept and slope had to be taken to put these in a linear form.

The use of the rate of rise and fall of the terrain and maximum grade of the profile as a basis for estimating earthwork quantities represents a new approach and while the resulting model is properly sensitive to variations in topography and design variations, the current version and data should be used with great care. While the basic structure of the contour line density model is felt to be valid and useful for estimating material quantities for low design standard roads, limitations in the existing data may reduce the immediate applicability. The methodology was developed on a somewhat limited data base and with an orientation towards very high design standard roadways. Five limitations are particularly relevant to the use of these data in a prototype highway cost model for low design standard roads.

1. The transferability of results from high design standard to low design standard roadways has not yet been shown. Profile grades for the different design standards and resulting earthwork volumes would be considerably different, particularly in rough topography.

2. The data were obtained using a one-point level cross-section, ignoring the effects of ground cross-slope, and will tend to underestimate volumes.
Figure 2.5 Linear Approximations of Earthwork Quantities vs. Contour Lines Crossed.
3. The original data were plotted based on 10-mile section lengths. Since the resultant curves were non-linear, care should be exercised in using segment lengths other than 10 miles.

4. Effects of such geologic conditions as rock and unsuitable material were not taken into consideration.

5. Profile lines were designed based on a balance of excavation and embankment quantities. In many cases, this is not normal design practice and an excess of excavation is planned.

Pavement

The selection and design of the pavement cross-section is an important cost component over which the designer can exert a relatively high degree of control. Although pavement costs do not typically constitute a majority of the total construction effort, critical tradeoffs with maintenance and vehicle operating costs involve the condition of the pavement surface.

Pavement design can be a complex and controversial topic. Most countries and regions have developed pavement design standards based on their own available materials and to satisfy their peculiar climate and traffic conditions. To allow for a wide variety of pavement designs, a specific design including material layer types and thicknesses is specified as part of the basic model input. Paved, gravel, and earth roads can be handled. Individual material layers can be bituminous concrete, bituminous macadam or roadmix, bituminous surface treatment, crushed stone, sandy gravel, and sand-clay or sand. The material types are utilized in estimating roadway deterioration and maintenance requirements. They are not directly used in the construction submodel. Additional material types such as cement or lime stabilization could be added.

The functional form of the pavement submodel is illustrated in Figure 2.6. The estimation of pavement costs is a straightforward series of calculations based on individual layer volumes. Initially, the total areas of roadway and shoulder surfaces are calculated. From these figures, the volume of each defined roadway and shoulder pavement layer can be determined. Source acquisition costs are determined, transport requirements are calculated, productivity rates applied, and labor and equipment costs calculated based on the required time.

Pavement thicknesses used in shoulder construction are generally thinner than those used under the traveled way. Therefore, separate layer thicknesses can be specified for the shoulder and roadway portion of the cross-sections. The top layer of the shoulder, if desired, can be a different material type than the top layer of the roadway. For example, a gravel shoulder can be used with a paved road. The base and subbase layers of the shoulders are assumed to be of the same type as those of the main roadway.*

*In the actual model calculations, the top shoulder layer is initially assumed to be of the same pavement material type as the roadway. If they are different, the quantity and cost figures are then revised.
Figure 2.6. PAVEMENT SUBMODEL.

**INPUT**

Road Design
- Alignment Length (m)
- Road Width \(i\) (m)
- Shoulder Width \(i\) (m)
- Thickness of each pavement and shoulder layer \(j\) (m)

**MODEL**

Calculate volume of each pavement layer
- Area\(_i\) = Length \(i\) \times Width \(i\)
- Vol\(_{ij}\) = Area\(_i\) \times Thick \(j\)

**OUTPUT**

Transport Factors
- For each layer \(j\)
  - Source Cost ($/m^3)
  - Transport Cost ($/Km/m^3)
  - Haul distance (Km)

Calculate source and transport cost
- S Cost\(_{ij}\) = Vol\(_{ij}\) \times Cost\(_j\)
- T Cost\(_{ij}\) = Vol\(_{ij}\) \times TCost\(_j\) \times Dist\(_j\)

Technology Data
- For each layer \(j\)
  - Productivity rate (m\(^3\)/Hr)
  - Labor rate ($/Hr)
  - Equipment rate ($/Hr)

Calculate time
- Time\(_{ij}\) = Vol\(_{ij}\) / Prod\(_{ij}\)
- L Cost\(_{ij}\) = Time\(_{ij}\) \times Labor\(_{ij}\)
- E Cost\(_{ij}\) = Time\(_{ij}\) \times E Cost\(_{ij}\)

Total Pavement Cost
- TC = \(\sum\_i \sum\_j\) T Cost\(_{ij}\) + \(\sum\_i \sum\_j\) L Cost\(_{ij}\) + \(\sum\_i \sum\_j\) E Cost\(_{ij}\) + \(\sum\_i \sum\_j\) S Cost\(_{ij}\)
A pavement can be specified as being of zero, one, two, or three material layers. Paved roads are generally a three-layer system; gravel roads are usually a single layer of gravel placed over the subgrade; and earth roads generally have no separate pavement layer. The cost of shaping the surface of an earth road can be considered part of the earthwork grading operation. Surface treatment, if utilized, can be defined as a separate material layer.

Pavement transport requirements are handled in the same way as for earthwork borrow. Each permanent material is assumed to have a unit acquisition cost at a source located away from the actual construction site. A unit transport cost is utilized. If these conditions do not exist for a particular material, the appropriate transport factor can simply be specified as equal to zero.

**Drainage**

Drainage requirements are highly variable depending on topography, climate, soil, geology and area hydrology. Where drainage requirements are high, provision of adequate drainage is important if the road is to remain open for traffic operation in all climatic conditions. Inadequate drainage can significantly increase required maintenance operations.

Drainage facilities include parallel roadway ditches, interceptor ditches, dikes, channels, culverts, and bridges. The drainage submodel is concerned only with estimating the cost of culverts. Parallel roadway ditches are included directly in the earthwork volumes estimate and bridges are normally included as part of the general structural requirements.

The drainage submodel is based on the doctoral thesis research of Armando Lago at Harvard University (1) and the Master of Science thesis research of Lloyd McCoomb at the Massachusetts Institute of Technology (2).

Drainage requirements were high in the region of interest to Lago and accordingly he developed a series of regression equations based on a fairly wide sample of international data. The lineal meters of drainage culverts required per kilometer of roadway are estimated as a function of terrain type, flooding condition, and roadway width. Lago's work is based on an earlier study by Pate (3).

The following three equations are used from Lago's study:

(1) **Flat Terrain:**

\[ DR = 6.0322 + 1.4472RW + 51.4005T_2 + 15.7256T_2^2 \]

\[ R^2 = 0.6606 \]

\[ T_2 = 1 \text{ if subject to medium or heavy flooding; } 0 \text{ if not} \]

\[ T_3 = 1 \text{ if subject to light to medium flooding; } 0 \text{ if not} \]
(2) Rolling Terrain: 
\[ \log DR = 1.0344 \log RW \]
\[ R^2 = 0.2317 \]

(3) Mountainous Terrain: 
\[ DR = 23.9379 + 7.7902 \cdot RW + 535.8799 \cdot T_1 \]
\[ R^2 = 0.7713 \]
\[ T_1 = 1 \text{ if mountainous rain jungle; 0 if not} \]

\[ DR = \text{lineal meters of drainage per kilometer of road} \]
\[ RW = \text{road width in meters} \]

The cost of drainage culverts is a function of culvert diameter. Lago's equations do not yield the expected number of culverts or the distribution of culvert sizes per kilometer. McCoomb examined a more limited sample of road projects than did Lago and found a consistency in the percentage distribution of the number of culverts per mile. In almost all cases, the distribution decreased monotonically with increasing culvert diameter. A frequency distribution as determined by McCoomb estimates the total length of each culvert size.

The overall drainage submodel, illustrated in Figure 2.7, integrates Lago's and McCoomb's contributions. McCoomb's distribution is based on five separate culvert sizes and is a composite based on 61 miles of projects. If fewer than five culvert types are defined, the stored frequency distribution is adjusted to correspond to the actual number of culvert types. Lago's equations are then used to estimate the total length of all culvert types per kilometer. This total length is then distributed between the defined culvert types using the stored frequency distribution.

Drainage transport requirements are primarily a function of weight and haul distance. The total drainage cost is a sum of the culvert acquisition cost and the transport cost. The placement cost is assumed to be included as part of the earthwork operation. Alternately, drainage placement costs can be incorporated into the source acquisition cost on the basis of cost/diameter size/length.

The exact shape of the frequency distribution of culvert diameters will vary with highway agency and local climate or terrain features. The assumed distribution can be easily modified by an organization to more closely match its practices.

The drainage submodel should be used with care. Additional research is needed to test the hypotheses, accuracy, applicability, and transferability of both Lago's and McCoomb's work. The research survey performed found relatively little work in the area of drainage as compared to earthwork, pavement, structures, and total cost estimating techniques. Accordingly, drainage requirements are not related to as many roadway design related parameters as desirable and drainage related cost tradeoffs between construction, maintenance, and operation are not adequately covered by the current submodel. Several drainage design techniques and formulae exist which are useful for the final design of culverts and other drainage.
Figure 2.7. DRAINAGE SUBMODEL.

**INPUT**

**Design Parameters**
- Alignment length (m)
- Roadway width (m)
- Number of culvert sizes (Max. 5)

**State of Nature**
- Topography
  - % Flat
  - % Rolling
  - % Mountainous
- Flood frequency switches T1, T2, T3

**Transport Factors**
- Haul distance (Km)
  - For each culvert size j
    - Source cost ($/m)
    - Weight (kg/m)
    - Transport cost ($/kgm/km)

**MODEL**

**OUTPUT**

**Frequency Distribution D_j**
- Number of Culverts vs Culvert Diameter
- Adjust frequency distribution if less than 5 culvert sizes defined
- Calculate total length of all culvert sizes/Km for each terrain type (Lago).
- Calculate total length of all culverts on alignment.
- Calculate total length of each culvert size j (McCoomb)

**Source cost** = $\sum_j L \times \text{unit source cost}$

**Transport cost** = $\sum_j L \times \text{unit weight} \times \text{unit transport cost}$

**Total cost** = Source cost + Transport cost
related facilities. These, however, usually require additional data on drainage areas and rainfall, are frequently empiric in their structure, and still do not satisfactorily relate drainage and roadway design.

Site Preparation

Site preparation involves clearing the site of all vegetation, trees, and obstacles and readying the site for the earthwork grading operation. Its physical difficulty is a function of topography, geology, vegetation, and climate. These conditions are specified to the model by specifying a percentage distribution of easy, normal and difficult conditions. This percentage distribution can be determined from aerial photos or mosaics of the alignment, length and the width of the area to be cleared.

The site preparation submodel is illustrated in Figure 2.8. The area in hectares of easy, normal, and difficult site preparation are determined using the input percentage distribution. Given the areas, productivities and cost functions are applied to determine labor and equipment costs. A summation yields the total site preparation cost.

Right-of-way acquisition and relocation costs can be considered part of the site preparation activity but are generally of little significance for low design standard roads in areas of interest to the Bank. In those cases where right-of-way costs cannot be ignored, an external estimate can be made and input to the model.

Miscellaneous Cost Items, Overhead and Supervision

The construction model explicitly accounts for site preparation, material volumes, pavement, and drainage costs. A portion of the total construction effort is allocated to components such as structures, fencing and other miscellaneous items. These items generally will consist of equipment as well as labor costs. In addition, costs must be allocated for administrative purposes including supervision and all labor and equipment costs that cannot be allocated to a specific cost component.

These two components are included in the construction submodel through specification of percentages of total construction cost devoted to each item, miscellaneous and overhead supervision. Further, a percent of labor can be applied to each cost to determine this component of the cost in dollar terms (Figure 2.9). A partial total is first calculated of the costs for site preparation, material volumes, roadway pavement, shoulder pavement, and drainage. The appropriate percentages are then applied to adjust this to a total cost representing all cost components. Given this total cost, the individual component and labor costs for the miscellaneous and administration categories are estimated.

Reconstruction and Upgrading

Two types of reconstruction or upgrading can be handled by the construction submodel:

Type 1 = Pavement Upgrading  
Type 2 = Roadway Reconstruction.
Figure 2.8 SITE PREPARATION SUBMODEL

**INPUT**

**Design Parameters**
- Alignment length (m)
- Clearing width (m)

**State of Nature, i**
- % Distribution of Easy, Normal, Difficult

**Technology Data**
- For each clearing type, (easy, normal, difficult)
  - Productivity Rate (Hectares/Hr)
  - Labor Rate ($/Hr)
  - Equipment Rate ($/Hr)

**MODEL**

Area\(_i\) = Length \times Width \times \%_i

**OUTPUT**

Total Site Preparation Cost

\[ TC = \sum_i \text{L Cost}_i + \sum_i \text{E Cost}_i \]
Figure 2.9. **TOTAL AND OTHER COSTS SUBMODEL**

**INPUT**

- Miscellaneous and Other Costs, $i = 1$
  - % of total cost, $i$
  - % labor, $j$

- Overhead and Supervision Costs, $i = 2$
  - % of total cost, $i$
  - % labor, $j$

**MODEL**

- Cost = Site Preparation +
- Earthwork + Pavement +
- Drainage

- Total Cost = Cost/(1-$\%_1 - \%_2$)
- Total Construction Cost

- $\text{Cost}_i = \%_i \times \text{Total Cost}$
- Component Costs

- $\text{L Cost}_j = \%_j \times \text{Cost}_i$
Execution of the model with type = 0 assumes new construction. A flow chart illustrating the macro reconstruction logic is shown in Figure 2.10.

Pavement upgrading consists of adjusting the existing roadway and shoulder dimensions, and either adding new (different) roadway and/or shoulder top pavement layers or repaving the existing roadway and/or shoulder layers with the same material types that are already being used. The associated cost items are pavement, other costs, and overhead costs. The roadbed is not modified and no additional drainage facilities are required so the site preparation, earthwork, and drainage submodels are not executed. The required input data are summarized in Figure 2.11.

Roadway reconstruction involves extension of the basic roadbed, but retaining the existing alignment and profile geometry. Input data, summarized in Figure 2.11, includes new roadway template and pavement descriptions, and new technology and cost data since these will likely change with time and also be different for reconstruction than for new construction. All cost items are re-estimated except site preparation costs. The site is assumed to be already cleared and no additional effort is required.

Reconstruction quantities are incremental in nature and are estimated as the difference between the total quantities required to build a new road to the upgraded standards and the quantities required to build the road to the standards before upgrading. This is done by first calculating the total quantities assuming the construction is entirely new, and then subtracting the accumulated total quantities from the previous construction period:

\[
\text{Reconstruction Quantity} = \text{Total Quantity}_{\text{new}} - \text{Total Quantity}_{\text{old}}
\]

Reconstruction productivities and cost data are applied to the estimated reconstruction quantities.

The model maintains a reconstruction array, RECON, which contains the total physical quantities for each of the construction operations. For new construction, this array is initialized equal to zero. At the end of new construction, the quantities in the reconstruction array are set equal to the calculated total quantities (Figure 2.10). During the subsequent reconstruction, the old quantity in RECON is subtracted from the calculated total quantity to determine the true incremental quantity. The reconstruction array is updated at the completion of the construction model so that it always contains the current "total" quantities.

An additional check is necessary in the pavement upgrading and reconstruction calculations (Figure 2.12). The top pavement layer for the roadway and shoulder may be either the same or a different material type than the existing top layer. If it is the same, then the standard reconstruction logic is applicable and an incremental quantity can be calculated as the difference between the new and old total quantities. If the top
Figure 2.10. MACRO RECONSTRUCTION LOGIC

INITIALIZATION

TYPE OF CONSTRUCTION

Roadway Reconstruction

TYPE = 2

New Construction

TYPE = 0

Pavement Upgrading

TYPE = 1

SITE PREPARATION

EARTHWORK

PAVEMENT

TYPE OF CONSTRUCTION

New Construction, or
Reconstruction, 2

Pavement Upgrading, 1

DRAINAGE

SUM APPROPRIATE INDIVIDUAL COST COMPONENTS

CALCULATE OTHER COSTS

SET THE RECONSTRUCTION QUANTITIES FOR THE NEXT RECONSTRUCTION OPERATION

END
Figure 2.11. Reconstruction Input

Pavement Upgrading
Roadway and Shoulder Dimensions
Pavement Data: Roadway and Shoulder
Haul Distances
Pavement Technology and Cost Data
Miscellaneous and Overhead Cost Items

Roadway Reconstruction
Roadway Cross-Section
Pavement Description
Material Haul Distances
Technology and Cost Data
Miscellaneous and Overhead Cost Items
Figure 2.12. PAVEMENT RECONSTRUCTION

1. Initialize for a pavement layer

2. Is this layer different material type from corresponding existing layer?
   - Yes: Set Reconstruction Volumes = 0.
   - No: Calculate layer volumes and costs, index to next pavement layer.
layer material types are different, then incremental quantities are inappropriate and a total volume of the new material layer is desired. In the latter case, the reconstruction volume is re-initialized equal to zero.

Technology and Productivity Packages

Three general procedures can be used to estimate the cost of a particular construction operation given an estimate of the physical quantities involved:

1. Application of an aggregate unit cost which includes both labor and equipment requirements.

2. The use of aggregate or package production and cost rates. An aggregated productivity rate for an operation determines the total time required for the particular operation. Subsequent application of aggregated labor and equipment cost rates yields the total operation cost.

3. The detailed simulation of the movement of individual pieces of equipment and associated manpower requirements to determine an estimate of time, equipment, and labor resources needed. Appropriate cost rates can then be applied to determine the total operation cost.

The second method, use of technology packages, is the most useful given the model objectives and is utilized in estimating the costs of all construction related operations. The necessary data are known to be available and material, labor, and equipment costs are not aggregated into a single figure.

The advantage of the single unit cost approach, e.g., dollars/cubic volume, is its simplicity and the almost universal availability of data in this form. The cost data maintained by most public highway agencies are in the form of unit costs. The major disadvantages of unit costs are their highly aggregated nature and the fact that they do not readily lend themselves to the analysis of alternative technologies.*

A detailed equipment movement simulation represents the opposite extreme of the unit cost approach. While it would provide the best analysis of alternative technologies and the most accurate answers of the three approaches, it is a costly and difficult method to apply to all construction operations and the data requirements are normally far in excess of those available. This approach, while desirable, was not feasible to develop and would result in an overly cumbersome model.

Use of aggregate or package productivity and cost rates represents a highly satisfactory compromise. It yields a sufficiently disaggregated set of answers, can be easily and readily utilized, and the data necessary for its use are available in both published and unpublished sources. An aggregated productivity rate for an operation determines the total time required for the particular operation. Subsequent application of aggregated

*In certain cases, only unit costs may be available. This data can be input to the model by specifying a unit productivity rate.
labor and equipment cost rates yields the total operation cost. The hourly cost of a "technology package" is the sum of the costs of all components contained in that package. The labor rate may not equal the actual pay rate, but is adjusted to account for such factors as efficiency. A package productivity rate is the combined average hourly productivity of all equipment and labor utilized to carry out the particular construction operation.

The standard costing equations take the following form where amt. is the total physical quantity involved:

\[ \text{Time (hrs)} = \frac{\text{amt.} (m^3)}{\text{Rate} (m^3/hr)} \]
\[ \text{Labor cost ($)} = \text{Time (hrs)} \times \text{L cost ($/hr)} \]
\[ \text{Equipment cost ($)} = \text{Time (hrs)} \times \text{E cost ($/hr)} \]

These equations are utilized in the site preparation, earthwork, and pavement submodels. Drainage culverts are assumed to be placed as part of the earthmoving operation and have only acquisition and transport costs; no productivities are specified. The two miscellaneous and administrative cost items are estimated as a percentage of total construction cost. While each of these latter costs can be separated into labor and equipment components, technology production rates as such are not appropriate.

**Transport Costs**

A major cost in the construction of low design standard roads in developing countries has been found to be the transport of materials from their source or point of entry location to the actual construction site. Haul distances may be long and the route may be difficult. Furthermore, the equipment required is often expensive and in short supply, leading to high unit transport costs. For all of these reasons, the estimation of transport requirements has been explicitly included in the earthwork, pavement, and drainage submodels. Site preparation is primarily an on-site activity and any transport requirements are assumed into the productivity and cost rates.

Two types of earthwork transport are required. First, any required borrow material (when embankment requirements exceed excavation requirements) must be moved from its off-site location to the embankment section where it is needed. Second, material must be moved along the length of the alignment from excavation to embankment sections. The first transport requirement can be estimated based on the total cut and fill volumes and is separately calculated in the earthwork submodel. The second type of transport movement requires a relatively detailed knowledge and analysis of the mass haul diagram and is not separately calculated in the highway cost model. An allowance for this type of transport, however, can be included in the earthwork productivity data.
Transport costs are established as a function of haul distance, the amount of material to be moved, and an estimated per kilometer transport cost on either a unit volume or unit weight basis. Transport costs are tabulated separately from material, labor, and equipment costs.

The cost function for a particular construction operation may occasionally consist of a fixed plus a linearly variable component rather than only variable components as now assumed. In this case, the transport cost item can be used to simulate the fixed cost and the normal productivities and labor/equipment costs used to cover the variable cost component.
References


Chapter 3. Maintenance Submodel

Purpose of Model

The maintenance model computes two types of information essential to the successful operation of the total cost model:

1. Maintenance Cost
2. Condition of Road Surface

These are computed for each year of the planning horizon. The maintenance cost is added directly to the total highway cost. The condition of the road surface is used as an input by the user model to estimate road user costs and this in turn is used to predict the volume of traffic attracted to the road. Thus, the surface condition predicted by the maintenance model affects the total highway cost indirectly, but very importantly, through its effect on road user cost.

Inputs - The four basic types of variables that affect the maintenance cost and surface condition are:

1. Environment
2. Traffic Demand
3. Characteristics of the Constructed Highway, and

The exact nature of a set of inputs needed to adequately describe each situation will depend on the type of design under construction. A gravel road, for instance, will require a different set of parameters to define maintenance policy than a paved road.

Outputs - Output from the maintenance model is of the same form regardless of the design. Maintenance costs are originally computed as the quantities of labor, equipment, and materials needed. These are converted to monetary costs based on the applicable factor prices. The accuracy of the predictions made by the maintenance model depends on the accuracy of the various relationships that make up the model. Most of these relationships were established with reasonable
confidence from the review of the literature. However, several of the relationships needed in the model have apparently not been empirically investigated. The model representation of these is based on the experience and judgement of the model designers. This somewhat limits the accuracy of the model. In general, however, the relationships for which the least information could be found were of only minor importance to the operation of the model.

To minimize the possibility that these unsupported relationships would seriously impair the accuracy of the model, a considerable amount of calibration work has been done with the model. For the situations investigated, the predictions of cost and road condition now compare reasonably well with what might be expected.

The costs predicted by this model are for actual maintenance activities. No supervision or overhead costs are included, except foreman wages. It is recognized that in some maintenance organizations these overhead costs can account for a major share of the total maintenance expenditures. However, changes in the overhead costs are influenced by many factors and investigation of the social, political and organizational factors that control the overhead costs is beyond the scope of this study. Only direct, traceable costs are considered. Supervision and overhead costs can easily be added to the predicted maintenance costs by the model user based on his knowledge of the local maintenance organization.

Four levels of maintenance output can be selected depending on the detail desired. The level of detail ranges from output that is limited to the total monetary costs for each year plus the accumulated totals of these costs to output that prints out a series of matrices which define how each unit of labor, equipment and material is expended during the year.

Roadway surface condition is computed by the maintenance model and described in terms of roughness, coefficient of friction and rolling resistance. These surface condition parameters are computed for a maximum of three subdivisions or seasons of each year. The length of each season is input by the user. The three subdivisions are: wet season (when earth roads become impassable and paved and gravel surfaces are wet a high percentage of the time), dry season (when earth and gravel roads need water for blading) and the rest of the year (when conditions are somewhere between the extremes). These three subdivisions provide a reasonably fine grain breakdown of the
year into more or less homogeneous seasons. Thus, the roadway surface is described by three parameters for up to three periods each year. These parameters can be used by the user cost model, along with vertical and horizontal alignment, etc., to compute user costs for each year.

The present user cost model does not use coefficient of friction in the computation of road user cost. However, it is expected that this refinement will be incorporated when coefficient of friction and its effect on road user cost can be predicted more accurately. The present structure of the maintenance model includes prediction of coefficient of friction to simplify future modification of the model.

Structure of Model

The structure of the maintenance model that evolved corresponds to the basic physical relationships that exist between the variables that affect maintenance and the resulting cost. These basic relationships, shown diagrammatically in Figure 3.1, are discussed below.

1. The function shown in Figure 3.1, as $F_1$, represents the deterioration rate of the highway. This establishes the relationship between the input variables (environment, traffic, design of highway, and maintenance policy) and the amount of deterioration expected. The amount of deterioration can be measured by such quantities as amount of cracking, number of potholes, cubic yards of soil deposited in ditches, and inches of vegetation growth. This relationship ($F_1$) is the most difficult part of the maintenance model to predict accurately.

2. The function shown as $F_2$ is the relationship between the quantities of deterioration discussed above and the quantities of maintenance action expended as a result. Maintenance action can be measured by tons of patching material placed, acres mowed, square yards of area bladed, etc. $F_2$ type relationships depend heavily on the maintenance policies and procedures being used. For instance, the area of pavement to be sealed may be much less than, equal to, or much greater than, the area of cracked pavement, depending on maintenance policies. Establishing this relationship is closely related to the problem of selecting and specifying maintenance standards. In the current model it is possible to specify the maintenance standards or policy. This makes it possible to adjust the relationship to meet local conditions. It also makes it possible to explore the effects of various alternative maintenance policies that may be advantageous.
Figure 3.1. Relationship Between Parameters and Cost

Input Parameters of Load, Environment & Design
(climate, traffic soil, design & maintenance standards, etc.)

$F_1$

Deterioration of Various Roadway Components
(potholes, erosion, cracking, weed growth, etc.)

$F_2$

Maintenance Action Required (tons of material placed, acres of weeds mowed, square yards of seal, etc.)

$F_3$

Maintenance Input Required
(labor, equipment and materials)

$F_4$

Cost of Maintenance
(dollars per mile)
3. The type of relationship shown as $F_3$ determines the expenditure of maintenance effort needed to accomplish the maintenance action found by the $F_2$ part of the model. Maintenance effort is measured in terms of labor, equipment and material in the current model. Finding the $F_3$ type relationships between actions needed and effort required is essentially a problem of determining the production rates for the various operations.

4. The $F_4$ type relationships are the appropriate unit prices for labor, equipment and material for the location involved. The proper selection of these unit prices is a separate economic problem in itself. Determination of these prices is beyond the scope of this study. The model is constructed to allow the unit prices to be specified by the model user based on the best information available. Either simple market prices or more difficult to determine economic opportunity costs can be used depending on the objective of the analysis.

In determining these four types of relationships, data from recent maintenance studies, maintenance records, and other records in the highway engineering literature were used. When only incomplete information could be found in the literature, engineering estimation techniques and judgement based on engineering experience were used to estimate the relationships. Relationships falling in this category include those concerning the surface condition of gravel and earth roads as discussed below and those concerning the effect of maintenance operations on PSI (pages A-4 through A-7). The problem of determining these relationships is discussed more fully in Alexander (14).

Discussion of the work involved in determining the maintenance relationships used in the maintenance model points out one of the inherent advantages of the model. The model is very flexible. Since many of the relationships affecting maintenance are explicitly represented, the model can take advantage of any additional information obtained. As additional information becomes available through research, or experience, the model can be updated to reflect this superior state of understanding without reconstructing the complete model. The capacity for adjustment or piecemeal improvement should be especially useful for adapting the model to local conditions.

An example of how the flexibility of the model could be used to advantage involves the mix of labor and equipment used for maintenance work. For the current model, a common crew-equipment mix was assumed for each maintenance operation. Using these assumed mixes, detailed assumptions were made of the productivity, fuel consumption and efficiency factors needed to simulate the maintenance operations and to estimate their costs. These assumptions are given in Appendix A.
The validity of cost predictions using these assumptions should not be affected substantially by a moderate variation from the assumed mix of men and equipment. If the equipment actually used is slightly larger than the size assumed in the model both cost per hour and production per hour normally increase. For instance, if a slightly larger loader is used, both production and cost per hour would be greater than assumed in the model. These would tend to cancel, and the cost per cubic yard of material loaded should not vary substantially. This canceling effect allows reasonable variations in the labor-equipment mix without seriously affecting the validity of the maintenance model. The model also provides for changing the production, and consumption characteristics of both equipment and labor if this type of detailed information is available to the model user. By adjusting the various factors that define capacity and fuel consumption of equipment, production of labor, assumed haul speeds, delays and efficiency rates, a wide range of crew compositions and strategies can be represented. This can be done without changing the maintenance programming, by appropriate adjustment of the assumptions defined as DATA statements in the maintenance model. A detailed description of these assumptions is given in Appendix A.

If however, the maintenance operations are expected to be done by crews and methods radically different from those assumed in the model, the model can be modified to accommodate this situation as follows: The productivity and consumption rates are determined for the new crew-equipment mix of interest. These rates are then used to replace the corresponding parts of the current model. This can be done without affecting the rest of the model. As the model is used in different situations and experience is gained, modules can be accumulated to represent the types of maintenance operations of interest.

The structure of the maintenance model was developed under the assumption that the production rates and cost per hour of maintenance crews would vary from country to country and would not usually be known. These rates and costs are developed within the model from more basic assumptions of individual capacities, consumption rates, efficiencies, etc. All or part of these assumptions can be easily adjusted to match a particular situation if knowledge of local conditions, crew make-up and efficiency are known in enough detail to justify the adjustment.

The model can also be easily adjusted to conform to local practice. Regravelling of gravel roads can be used as an example. Assumptions in the current model define a regravelling operation that is typical in some areas. These include assumptions for:

a. Depth of existing surface to be loosened by motor grader.

b. Depth of new gravel to be placed.
c. How much the moisture content of loose gravel must be raised to allow for efficient compaction.

If the current assumptions for any of these does not match local practice, they may be changed by replacing one DATA card for each change. The model will then simulate the local regravelling operation. No other changes need be made to the model for this type of adjustment.

An operation can even be eliminated. For example, if local practice does not include watering (maybe it is always done during a wet season), the needed change in moisture content (WA2) can be set equal to zero. The maintenance costs normally computed for this operation will equal zero.

In summary, the maintenance model is currently programmed to simulate what are thought to be typical maintenance operations being done by common crew-equipment mixes of reasonable efficiencies. However, if the model user has information on the details of local practice, organization or efficiency he may take full advantage of this information by making one card change to the DATA statements of the model. If this information is available, and intelligently used, the maintenance model is capable of simulating a wide range of local conditions.

Detailed Description of Model

The maintenance model is made up of sections to deal with four categories of maintenance, plus a section that sums the quantities of labor, equipment and materials and finds the monetary costs. For each of the four categories of maintenance activity (surface, drainage, shoulder, and vegetation control) the model explicitly represents the four types of physical relationships defined in Figure 3.1. That is, the model deals with the problem of finding deterioration, quantity of work, required input, and finally monetary cost, as individual parts of the actual physical sequence. The sequence of operations used in the maintenance model are illustrated in Figure 3.2.

The basic structure and operation of each of the sections of the maintenance model are described below. This description in conjunction with Appendix A (containing definitions and assumptions) and the separate program documentation submitted with this report furnish a comprehensive guide for model users.

The emphasis in this discussion is placed on the problem of surface maintenance. This emphasis coincides with the distribution of cost for maintaining low cost roads. Surface maintenance is usually responsible for over half of the maintenance cost and in some extreme cases can account for practically all of the expenditures. A second
Figure 3-2: (page 1) Flow Diagram of Maintenance Model
Figure 3-2 (page 2): Flow Diagram of Maintenance Model
reason for concentrating on surface maintenance is the obvious tradeoff potential with construction and user costs. Other types of maintenance costs also provide opportunity for tradeoff, but usually involve smaller amounts of resources.

Paved surface maintenance is handled in the model by a routine that simulates the cycle of deterioration and repair of asphaltic pavement. This is done in the four basic steps illustrated in Figure 3.1. Deterioration (F1 type of relationship in Figure 3.1) is predicted as a function of equivalent axle loads, maximum axle load used, pavement characteristics, and soil type. The equations used to predict this deterioration are of the basic form developed from a study of AASHO road test results (See Appendix A). Several modifications have been made to allow better prediction of deterioration rates for low cost bituminous roads under light traffic.

Deterioration is initially predicted in terms of the AASHO concept of serviceability (present serviceability index-PSI). This serviceability measure is related to three measurable characteristics of the surface: slope variance (SV), rut depth (RD), and amount of cracking and patching (C + P) by the equation (1):

\[ \text{PSI} = 5.03 - 1.91 \log(1+SV) - 0.01 \frac{C + P}{F1} - 1.38 \times RD^2 \] (3-1)

Deterioration is predicted as a drop in AASHO serviceability, PSI, for each year of the analysis period. The model estimates deterioration as a function of equivalent axle loads, pavement characteristics, and environment. The equation for estimating deterioration was developed from a regression analysis of AASHO road test results (6). Since the model is to be used over a wide range of conditions, the equation found by regression analysis was modified to allow adjustment to local conditions. The equation that resulted is of the form:

\[ \Delta \text{PSI} = K \times S \times V \] (3-2)

in which \( \Delta \text{PSI} \) is the uncorrected annual deterioration after \( V \) applications of an equivalent axle load, \( S \) is the slope of the deterioration curve (Figure 3-4), and \( K \) is a calibration factor for the rate of deterioration which can be used to adjust for unusual local conditions such as very heavy rainfall or flooding.

The deterioration rate, \( S \), can be approximated by the following equation (6):

*Numbers in parentheses refer to references at end of this chapter.
\[ S = \alpha 10^{-\beta SN'} \]  

(3-3)

where \( \alpha \) and \( \beta \) are dependent on \( P \), the equivalent single axle load used, as follows (6):

\[ \alpha = 0.5 \times 10^{0.078 P-6} \]  

(3-4)

\[ \beta = 0.35 + 0.005 \times P \]

and \( SN' \) is the effective structural number or thickness index, of the pavement found by adjusting the actual thickness index, \( SN \), to take subsoil into consideration by the following equation. (7):

\[ \frac{SN'}{SN} = \frac{\log(CBR_1)}{\log(CBR_0)} \]  

(3-6)

where thickness index, \( SN \), is a measure of pavement strength found by taking the sum of the products of layer thicknesses and layer unit strengths thus:

\[ \bar{SN} = a_1 d_1 + a_2 d_2 + a_3 d_3 \]  

(3-7)

where \( d_1, d_2, \) and \( d_3 \) are the depths of the component layers of the pavement. And the coefficients \( a_1, a_2, \) and \( a_3 \) are weighting factors (functions of strength) for the corresponding layers. The values found during the AASHO road test are used for these coefficients.

\( CBR_1 \) is the California Bearing Ratio of the subsoil of interest.

\( CBR_0 \) is the California Bearing Ratio of the subgrade soil used in the AASHO Road Test, on which these relationships are based.

The deterioration caused by the passage of a vehicle depends on the weight and physical configuration of the wheels and axles of the vehicle. In order to obtain a manageable measure of this capacity for damage, the concept of equivalent axle load, \( P \), is used. This is a common technique in pavement design. Each axle loading that actually passes over the road is converted to the equivalent number of 18,000 pound single axle loadings that would cause the same amount of damage. Using this method, the total traffic loading can be represented as a single number of equivalent single axle loads. The variable \( V \) used in the deterioration equation represents the number of equivalent 18,000 pound single axle loads using the surface during the year.

The model computes \( V \) as a function of the number and type of vehicles using the road. This information is specified by the model user based on traffic prediction. The computation of \( V \) can be represented as follows:
When \( b_i \) represents the number of type \( i \) vehicles using the road during the year being analyzed, \( V_i \) is the weighting factor to convert one type \( i \) vehicle to the number of 18,000 pound single axle loads that would cause the same pavement damage. (The present model can handle up to seven basic vehicle types.) \( V_i \) is found by the equation (7).

\[
V_i = (0.1 \text{ WS}_i - 1.8) + (0.7 \text{ WT}_i - 2.2)
\]

where:

- \( \text{SA}_i \) = number of single axles on type \( i \) vehicles
- \( \text{TA}_i \) = number of tandem axles on type \( i \) vehicles
- \( \text{WS}_i \) = weight in Kips of the single axles on type \( i \) vehicles
- \( \text{WT}_i \) = weight in Kips of the tandem axles on type \( i \) vehicles

The model has now been discussed up to the point where uncorrected annual deterioration can be computed as a function of the input variables that define pavement design, traffic, and subsoil. Most of the relationships presented were developed from regression analysis of AASHO Road Test data. The AASHO Test was an accelerated test that lasted approximately two years. As a result of the short test time, it is likely that very little of the deterioration observed was a result of time dependent variables. However, there is ample evidence that time is a factor in the deterioration of asphalt pavements. Aging of asphalt mixtures has been well documented (8,9). Swelling and shrinking of subsoil also often plays an important role in the performance of the pavement. In some instances this movement of the underlying soil overshadows traffic damage as a cause of deterioration (10). To simulate time dependent deterioration the uncorrected annual deterioration, \( \Delta \text{PSI} \), is modified by adding an annual deterioration factor. Since there is little information on the function governing time dependent deterioration, a constant factor is used to represent this damage.

\[
\Delta \text{PSI}' = \Delta \text{PSI} + \text{AGE}
\]

Thus, the annual drop in PSI is increased by a constant increment each year independent of traffic damage. The \( \text{AGE} \) factor may be determined by the model user to approximate local conditions and experience. It is suggested that this factor be approximately 0.1 units of PSI per
year unless information is available to determine another value. A value of 0.1 will simulate major surface deterioration in 20 to 30 years even if very little traffic is present.

Another adjustment built into the model allows deterioration rate to increase with age. Uncorrected deterioration, ΔPSI determined by equation 3-2 is a linear function of equivalent axle loads, V. However, plots of serviceability as a function of axle loads often indicate an increasing rate of deterioration during service life. To simulate this type of deterioration function, the annual deterioration production can be modified as follows:

\[ ΔPSI'' = ΔPSI' \times (1 + I)^{YR} \]  

where YR is the age of the pavement in years and I is the factor which can be adjusted to correspond to local experience. A value for I in the range of 0.03 to 0.05 appears to simulate the increase in rate with load application found on some sections of the AASHO road test. If experience indicates that serviceability is a linear function of load application, the value of I should be set equal to zero to eliminate the effect of this adjustment mechanism.

Substituting equation 3-2 and 3-10 into equation 3-11 yields:

\[ ΔPSI'' = (AGE + K \times S \times V) \times (1 + I)^{YR} \]  

This is the equation used by the model for estimating the annual drop in serviceability. The new surface condition is predicted by:

\[ PSI_1 = PSI_0 - ΔPSI'' \]  

where PSI_0 is the serviceability at the start of the year and PSI_1 represents serviceability after deterioration but before any maintenance work is done. Using this new level of serviceability, the degree of deterioration measured in terms of skew variance (SV), rut depth (RD), and amount of cracking and patching (C + P) is found using the following relationships:

\[ SV = \frac{10^{-0.031PSI^2 - 0.54PSI + 2.3}}{1.0} \]  

\[ RD = -0.03 \times PSI^2 + 0.09 \times PSI = 0.32 \]  

\[ (0.3 \times PSI^3 - 1.3 \times PSI^2 - 6.2 \times PSI + 29)^2 \text{ if } PSI < 4.3 \]  

\[ (C+P) = 0 \text{ if } PSI \geq 4.3 \]
Equations 3-14, 3-15 and 3-16 were found by polynomial regression analysis of data collected during the AASHO Road Test (1). Equations 3-14 and 3-16 are based on data from 73 road sections. Forty-nine of these sections were on existing state roads and 24 were on road test loops. The coefficient of correlation found for equation 3-14 is .91 and the F test indicates that the regression is significant at the 1.0% level. Equation 3-15 is based on data from the forty-nine state road sections. The 24 sections on the road test loops showed unusually deep rutting and were not considered to be representative of normal rutting behavior under more usual traffic conditions. The correlation coefficient of equation 3-15 is .61 and the F test indicates significance at the 10.0% level. The coefficient of correlation found for equation 3-16 is .68 and the F test indicates significance at the 2.5% level.

The amount of maintenance work to be done during the year (F2 type relationship) is determined in the model by the predicted depth of rut, RD, the change in C + P (new cracking) and the maintenance policy specified. This policy is selected by the model user and specifies what maintenance should be done for different degrees of deterioration. Detailed definitions of these maintenance policies are given in Appendix A. With the four variables which the model user can select to represent pavement maintenance, a wide range of maintenance policies can be specified.

Once the amount of maintenance to be done for the year is determined, the model computes the quantities of labor, equipment, and the materials necessary to do the work (F3 type relationship). This is done by estimating techniques using productivity and consumption rates found during the review of literature. These productivities and consumption rates are believed to be reasonable for typical maintenance operations. The definition of these rates as well as the values used in the current model are given in Appendix A. These values can easily be changed by the model user to improve the accuracy of the model, if additional information of knowledge of non-typical or local conditions is available.

After the quantities of labor equipment and materials are determined, the model computes the expected maintenance cost by multiplication with the appropriate unit costs which have been furnished by the model user. (F4 type relationship)

This completes the operations needed to predict pavement maintenance costs for one year, but the model must also predict the surface condition for use by the user model. Of the three surface condition parameters, rolling resistance is assumed to stay constant for paved roads; roughness is predicted by its correlation with PSI, and coefficient of friction is estimated by the age of surface and climate conditions as shown in Figure 3.3.
Figure 3.3. Coefficient of Friction Versus Time.

*Figure 3.3 is based on empirical information on the range of coefficient of friction found on existing highways. The estimated reduction of coefficient of friction with age is based on evidence that traffic wear and "bleeding" of asphaltic mixes reduce the coefficient during the service life. See references 2 and 3.
A central feature of the pavement maintenance routine is the prediction of the serviceability level for each year of the analysis. This produces a prediction of how the general serviceability of the surface varies during the analysis period. This continuous prediction is made by estimating both the annual deterioration due to traffic, age, and environment; and the improvement resulting from maintenance done during the year. Prediction of deterioration has already been discussed. Prediction of improvement as a result of maintenance is based on the amount and type of maintenance done during the year and the current level of serviceability. The detailed assumptions on which these predictions of improvement are based are described in Appendix A. This method of simulating the deterioration of a paved surface results in a variation of serviceability with the time similar to Figure 3.4.

Both the amount of maintenance to be done in a particular year of the analysis period and the roughness of the road in that year depend on this prediction of serviceability. Basing the amount of maintenance work to be done on a measure of the road condition results in a model which simulates some of the feedback characteristics of a real system where condition also influences maintenance work and maintenance work influences condition.

Roughness based on serviceability completes another dynamic feedback loop and results in closer simulation of the real system:

1) Roughness is used by the user model in road user cost prediction.
2) Road user costs affect the amount of traffic that will use the road through the price elasticity of demand.
3) The amount of traffic using the road affects the prediction of deterioration, completing the loop.

The model relies heavily on data from the AASHO Road Test to predict the type and degree of deterioration to be expected in bituminous surfaces as a function of traffic and pavement design. Although the road test represents the most complete source of this type of information, the patterns of deterioration may be substantially different in some geographical areas of interest. The type and degree of physical deterioration resulting from traffic loads should be established for each area in which the model is used. However, until this information is developed, the AASHO data appears to be the best available and can be used for preliminary work with the model. As the relationships needed are found by research or experience in developing areas, this part of the model can be modified to reflect this more accurate information without disturbing the operation of the rest of the maintenance model or the overall model.
Figure 3.4. Example of How PSI Varies as a Result of Deterioration, Routine Maintenance, and Resurfacing.
Gravel surface maintenance is simulated in a different manner than paved surface maintenance. Blading is the basic form of maintenance for gravel surfaces. The frequency of blading is specified by the model user as either a function of time (blading per year) or a function of traffic equivalent (vehicles per blading). Both maintenance cost and surface conditions are based primarily on the frequency of blading.

Maintenance cost is computed by a series of steps similar to the steps $F_0$ through $F_4$ in Figure 3.1. By specifying the frequency of blading, the model user eliminates the need for the model to predict deterioration. Instead, by using the specified bladings per year, traffic volume, and width of surface the model computes the area to be bladed per year ($F_2$ type function.)

To find the labor, equipment and material needed and the monetary cost of these resources requires $F_0$ and $F_2$ type functions similar to those used for paved surfaces. The assumptions used in these computations are given in Appendix A.

However, the relationships needed to estimate surface condition of gravel and earth roads are mostly based on the judgement of the model designers. Since these relationships are open to question they are presented in graphical form in figures 3.5 through 3.10 to illustrate the assumptions in the current model.

The relationships needed to predict roughness (Figures 3.7 and 3.8) are of major importance to the accuracy of the total cost predictions because of the effect of roughness on vehicle operating cost. Fortunately, some information is available to help establish these relationships. The range of roughness is found on existing unpaved roads has been investigated (11,12). There is also information on the blading frequency used in practice (5). These two types of information were used to estimate what the relationship between blading frequency and roughness might be.

The relationships needed to predict rolling resistance and coefficient of friction are of much less importance to the successful operation of the model as they have a much smaller effect on road user cost than roughness. This is fortunate since the relationships illustrated in figures 3.5, 3.6, 3.9 and 3.10 are based on very little empirical information(13). The relationships shown probably represent a reasonable range of values for rolling resistance and coefficient of friction. Their correlation with blading frequency is thought to be a reasonable assumption but is not supported by empirical evidence.

*Studies are now being planned which will help to establish the relationships illustrated in Figures 3.5 through 3.10.*
Figure 3.5. Rolling Resistance Versus Blading Frequency for Gravel Roads. (Reference 13)
Figure 3.6. Coefficient of Friction Versus Blading Frequency for Gravel Roads (References 2 and 3)
Figure 3.7. Roughness Versus Blading Frequency for Gravel Surface. (References 5, 11 and 12)

Figure 3.8. Roughness Versus Blading Frequency for Earth Surface. (References 5, 11 and 12)
Figure 3.9. Rolling Resistance Versus Frequency of Blading for Earth Roads (Reference 13).

Figure 3.10. Coefficient of Friction Versus Frequency of Blading for Earth Roads (References 2 and 3).
If regraveling is not specified as part of the maintenance policy, the model assumes that the road reverts to an earth road when less than seven centimeters of gravel remain on the surface. The model converts the road type designation to earth and the remainder of the analysis will be made on the assumption that the road has an earth surface.

**Earth surface maintenance** is basically the same as gravel surface maintenance except for the regraveling operation. The major difference between gravel and earth roads, as defined in this study, is that while gravel roads are assumed to remain passable all year, earth roads become impassable for some fraction of the year. An effort was made during this study to find a reliable way to predict the fraction of the year that an earth road would be passable. This could reasonably be expected to be some function of soil type, rainfall, type of vehicle used, maximum weight of vehicle, grades of roads and maintenance policy in effect. However, very little information could be found to help determine this relationship. If rolling resistance and coefficient of traction could be predicted for earth roads under adverse conditions, it might be possible to predict when the road would become impassable using the vehicle behavior routines in the user model. But realistically predicting rolling resistance and coefficient of traction under these conditions also appears to be impractical. As a result, it was concluded that the most realistic way to determine the fraction of the year that an earth road was likely to be impassable is based on the behavior of similar roads in the area. This fraction is part of the user input in the current model.

**Drainage maintenance cost** is predicted by a series of calculations that follow the general procedure illustrated in Figure 3-1. Deterioration is quantified as the amount of sediment deposited in the ditches and drainage structures during the year. This is estimated as a function of rainfall, type of terrain, and steepness of the cut and fill slopes. The sediment estimating procedure is described in detail in Appendix A. Rainfall, terrain and slopes were the parameters that could be identified in the literature affecting the amount of sediment deposited. It seems reasonable to assume that type of soil and land use also play an important role in how much soil is deposited. However, no information could be found about the effect of these variables that could be used to establish the relationship. This may be a case where a modest amount of research could produce information of value to maintenance prediction in an area now nearly vacant.

After the deposited sediment is estimated the model determines whether it will be removed or not depending on the maintenance policy specified. There is no provision in the model for simulating the removal of only part of the sediment deposited. Although removal costs are computed every year, the productivity rates are based on a reasonable depth of sediment and reasonable crew size. This approximates the costs of an operation that may be done every few years. The
gradual sedimentation and periodic removal was not considered necessary for the purposes of the model. The required input of labor equipment and material and the monetary cost of these inputs are estimated by procedures similar to the corresponding steps for surface maintenance. The detailed assumptions governing this estimating procedure are defined in Appendix A.

Shoulder maintenance depends on the type of shoulder involved. Paved and unpaved shoulders are handled by different routines within the model. Maintenance for paved shoulders is estimated basically on the assumption that the maintenance required will be proportional to the maintenance required on the adjacent paved roadway. It is also assumed that more shoulder maintenance will be needed if the traveled surface is narrow (5). As a result of these assumptions, maintenance of paved shoulders is estimated as a function of the maintenance required on the roadway and the width of that roadway. The detailed assumptions are given in Appendix A.

If the shoulder is unpaved, the maintenance cost is estimated as a function of traffic volume and width of traveled roadway. A minimum of one blading a year is also assumed in order to simulate minimum maintenance required to avoid direct damage to traveled surface from erosion, encroaching vegetation, etc.

Vegetation control is not usually a major part of maintenance cost. For this reason, the routine that estimates this cost is somewhat simpler than the other routines. No attempt is made, in the model, to estimate vegetation-growth (which corresponds to the measure of deterioration in this case). Instead, the number of mowings to be done each year is specified by the model user based on his judgment and knowledge of the area. The amount of labor, equipment and materials required and their monetary cost is estimated by the model. These costs are estimated as a function of number of mowings per year, width to be mowed, and the productivity assumptions given in Appendix A.

Summary

After costs for these four types of maintenance are estimated, the model totals the quantities of labor, equipment and material and the resulting costs. These totals are then used by the main subroutine to compute the accumulated total discounted and actual costs for the analysis.

Most of the relationships needed for the maintenance model have been determined with a fair degree of confidence, based on information found in the literature and on engineering estimating procedures. Unfortunately, some of the needed relationships could not be as well supported. Instances of these have been noted throughout this chapter.
Where little could be found about the nature of a needed relationship, indirect information, logic, and judgment have been used to establish the function as accurately as possible. This has been necessary in order to produce a working model within the time and resource limits of this study. It is believed that these functions are reasonable approximations of the actual relationships and permit realistic model operation. Preliminary work with the model supports this view, since behavior has been generally realistic for the range of situations simulated.

However, until further research more accurately establishes the nature of these relationships, this limitation on the accuracy of the model should be recognized. The present model does provide a conceptually sound framework which can easily be modified to incorporate the additional information developed by future research.
REFERENCES


Chapter 4. Vehicle Operating Cost Submodel

The basic element in the Vehicle Operating Cost Submodel is the prediction routine which has been designed to compute the resources consumed in operating a specific vehicle over a homogenous roadway section. It is based on a thesis by Guenther (5). This routine is used iteratively as the main element in the vehicle cost submodel to determine the cost of operating in different time periods and on different sections of the highway with different vehicle types. The physical resources predicted -- labor, fuel, tires, vehicle life, and the time value of capital invested in vehicles and cargo-- are then converted to total costs using unit prices supplied by the analyst. Summary output expresses these resource requirements for the vehicle fleet in terms of labor, material, and equipment costs. Additional output describing predicted performance and cost of each vehicle on each roadway section is optionally available.

Roadway characteristics which influence vehicle operating costs are vertical profile, horizontal alignment, and surface condition. Vertical profile and horizontal alignment are output from the construction submodel while surface condition is output from the maintenance submodel. No effects of traffic on operating cost are considered because this model is designed for the evaluation of roadways with traffic volumes low enough to preclude any significant amount of vehicle interaction.

The steps in the basic routine are:

a. Estimate the time required to traverse the segment.
b. Estimate the fuel requirement.
c. Estimate tire wear.
d. Estimate vehicle maintenance.
e. Estimate vehicle depreciation.

A key element is prediction of the time required to traverse a segment. This part of the vehicle operating cost model is relatively complex because there are a number of factors which influence average trip time. The approach used is to assume that each factor operates independently to limit vehicle velocity. The factors which are considered to limit velocity are:

a. The design speed of the vehicle itself, i.e., the speed determined by maximum engine operating speed, transmission and differential gear ratios, and tire size. This speed may be included in the manufacturer's specifications, or calculated from them.
b. The roughness of the roadway surface and its interaction with the vehicle suspension system.
c. The horizontal alignment of the roadway (curvature).
d. The horsepower available to overcome rolling resistance of the roadway surface and to lift the vehicle on uniform rising grades.

e. The combined effects of available horsepower and momentum which determine average speed on rolling segments.

Although there are several ways these factors may be assumed to affect vehicle velocity, it has been assumed in this model that only one factor at a time limits velocity. The idea that velocity could be expressed as a linear function of these factors is specifically rejected. Hence, least squares regression as a method of obtaining a velocity function is rejected. The accepted approach is to consider each factor as an independent constraint on maximum velocity.

Linear additive functions such as the regression equations derived by Bunce and Tresidder (2) are not used because the co-efficients must be estimated from non-experimental data. In such a non-experimental situation causality may be quite different from that suggested by the statistically estimated relationship (1) (3). In this case, the factors which may be assumed to independently constrain vehicle speed will also be determined by speed. For example, curvature will limit vehicle speed but, if speed is already limited by rise and fall, the design engineer will usually permit greater curvature. As a result curvature and speed will be correlated but causally speed may determine curvature rather than curvature determining speed. Causally speed may be independent of curvature in this example. For design purposes a causal relationship must be obtained. Because these problems of causal inference exist and also because available data does not take vehicle characteristics into account, the regression approach was rejected for estimating vehicle speed.

Computation of estimated fuel requirements, tire wear, maintenance, and depreciation all depend on vehicle velocity and, hence, follow the determination of limiting velocity. After limiting velocity is determined, fuel requirements are estimated as a function of the vehicle weight and the roadway profile and surface. Then maintenance, tire wear, and depreciation are computed.

Figure 4.1 is a macro level flow chart of the vehicle operating cost submodel. For computational efficiency the computation of vehicle operating characteristics are divided into three groups -- characteristics which are determined only by the roadway geometry and, hence, are constant for all vehicles and seasons; characteristics determined by the interaction between the vehicle and roadway geometry but not influenced by the season; and, characteristics influenced by the seasonal variations in the surface condition as well as the vehicle and the roadway geometry. The model first computes resource requirements per vehicle kilometer. From these the market cost per vehicle is computed and thus cost is used in conjunction with the demand schedule to compute the traffic volume. Total annual operating costs for this plus vehicle type is then computed. These steps are repeated for each vehicle type.

Unlike the other submodels, the vehicle operating cost submodel requires two sets of unit prices as input. One is a set of social opportunity costs
Figure 4.1. Vehicle Operating Cost Flow Chart

Start

Compute factors which are constant for all vehicles and all seasons or subperiods (1)

Compute factors which are unique to this vehicle but constant for all seasons or subperiods. (2)

Compute factors which are unique to this vehicle and season or subperiod. (3)

Compute cost per vehicle kilometer (4)

All seasons or subperiods (6)

Compute number of vehicle trips per year (7)

Compute total annual costs for this vehicle (8)

All vehicles (9)

Compute total labor, materials, and equipment costs and incremental willingness-to-pay for the year (10)

End (11)
comparable to those used in the other submodels to value other resources. The second is a set of market prices used to calculate the cost which vehicle operators perceive. This perceived cost is used along with the demand schedule to estimate traffic volume.

The perceived or market cost also enters into the evaluations through the calculation of incremental willingness to pay. Incremental willingness-to-pay is computed so that the total cost of roads with different volumes of traffic (but not different demand schedules) will be comparable. Reductions in travel volume due to higher operating cost are reflected in a reduction in willingness-to-pay which is added to the overall cost. Similarly, an increase in willingness-to-pay is treated as a benefit or negative cost.

The following paragraphs describe each major operation in the model. The first twelve operations involve formulas originally developed in U.S. units. They are expressed in U.S. units in the program and later converted to metric units so that all input and output is metric.

**Step 1.** Compute maximum velocity due to curvature

\[ V = (\frac{5730}{\text{ADC}})^{0.5} \times 1.55 \]

\( V = \text{velocity limit in miles per hour} \)

\( \text{ADC} = \text{Average Degree of Curvature} \)

Thus, the velocity limit due to loss of traction on curves is expressed as a function of average degree of curvature. The relationship is derived from the standard highway engineering relationship

\[ e + f = \frac{V^2}{15 R} \]

where

\[ R = \frac{5730}{\text{ADC}} \text{ is the average radius of curvature} \]

\( e = 0 \text{ superelevation factor} \)

\( f = .16 \text{ coefficient of side friction} \)

If superelevation is planned or if a different coefficient of side friction appears more appropriate for the specific situation, this relationship might be changed. Velocity is computed in miles per hour and then converted to kilometers per hour.

* The degree of curvature is the central angle which subtends a 100-foot chord. The average degree of curvature in a mile is the sum of the degrees of curvature divided by 52.8.
If roadway is single lane, compute maximum velocity due to sight distance on curves

\[ V = \left(\frac{5730}{ADC}\right)^{0.47} \times 1.47 \]

This velocity limit is due to stopping sight distance and also is derived from standard engineering relationships. It is assumed to apply only on single lane roads where stopping for an oncoming vehicle would be necessary. A single lane road is defined in this program as one which is less than three meters wide.

Step 3. Initialize vehicle counter

An indicator is set to identify the specific vehicle for which all the following calculations apply.

Step 4. If road has continuous grade, go to six

The input data is checked to determine whether the roadway profile is rolling or a continuous grade. If rolling, the fuel requirement estimator in Step 5 which is independent of season will be used. If continuous, a different relationship will be used.

Step 5. Compute fuel consumption for a road with rolling grade

\[ \text{Fuel} = [K2 \times (\text{Gross Vehicle Weight}/1000)^{K3}] \times K4 \]

Fuel consumption on rolling grades is estimated using the formula originally developed by Saal (8) and modified by Roberts and Soberman (7). The parameters of this model were originally estimated from data collected in 1948 from the operation of trucks on paved road segments of 1.04 to 149.39 miles in length. The parameter, \( K4 \), is used to adjust fuel requirements for unpaved surfaces and did not appear in the original work. The parameters \( K2 \) and \( K3 \) are functions of the rise and fall of the roadway.

Step 6. Initialize subperiod counter

The subperiod counter is used to identify whether the period is the dry season (period 1), the wet season (period 2) or the impassable season (period 3). Rolling resistance on unpaved roads changes from season to season. If data becomes available, the seasonal breakdown can also be used to estimate the costs of roads being impassable. However, no such capability now exists in the model.

Step 7. Is length of subperiod zero? No, go to 8; yes, go to 21

The total period, usually a year, may be divided into three subperiods or seasons of arbitrary length. Computationally this divides
anticipated traffic volume into three parts and the cost per trip in each segment is computed separately. If the length of the season is zero, no traffic flows in that period and no calculations are made.

**Step 8.** Compute maximum velocity due to surface roughness

The velocity limit due to surface roughness is obtained from a table look-up and linear interpolation. There is one table for heavy vehicles and one for light vehicles. The tables are based on observations by Bunce and Tresidder (2) in Jamaica but their range has been extended to incorporate rougher roads than those observed in Jamaica. It will be relatively easy to change these tables as new data become available from field research.

**Step 9.** Compute maximum average velocity due to vertical profile.

For rolling profile:

\[
V = \frac{60}{K_0 + K_1 \left(0.9 \times \text{Installed Horsepower} \right)}
\]

or, for continuous grade:

\[
(375) (0.9) (\text{Installed Horsepower}) = V(GVW)G + V(GVW)C_r(1 + \frac{V}{WF}) + C_a AV^3
\]

**GVW** = Gross Vehicle Weight

**G** = Tangent Gradient

**G** is + for gradient adverse to travel

**G** is - for gradient favorable to travel

**C_r** = coefficient of rolling resistance

**WF** = empirical weight factor

**C_a** = empirical coefficient of air resistance (aerodynamic drag)

A cross sectional area of vehicle

The computation of average velocity limits due to the vertical profile is divided into two separate parts depending upon whether the roadway is rolling or whether there is a constant grade for the entire section under consideration. If the roadway is rolling and momentum from the descent on one hill can be used to climb the following hill, the rise-and-fall model as developed by Saal (8) and modified by Roberts and Soberman (7) is used. It is based upon the rise and fall of the roadway. The two empirical constants were
derived from operations on paved roads. The model, so far as we are able to determine, has never been calibrated for unpaved surfaces.

For constant grades, we use the equilibrium velocity model which directly incorporates resistance to grade, rolling resistance, and air resistance. This model seems to be well suited to computing velocities on soft earth roads and on long, steep grades. For this model, the coefficient of rolling resistance is input from the maintenance submodel. The weight factor, WF, and the air resistance coefficient, C, are provided. The vehicle cross sectional area, A, is calculated from the vehicle height and width. The equation is solved iteratively to the nearest five miles per hour.

Step 10. Find the limiting velocity

Each of the velocity constraints, vehicle design speed, curvature, roughness, and horsepower are examined and the minimum is taken as the predicted operating velocity.

Step 11. Is grade continuous? Yes, go to 12; no, go to 13

Step 12. Compute fuel consumption

Fuel = HP/V X .085, for gasoline
Fuel = HP/V X .05, for diesel

HP = horsepower actually used
V = velocity

Fuel consumption expressed in gallons per mile in the continuous grade case is computed by multiplying a specific fuel consumption parameter by horsepower hours per mile. The horsepower hours per mile is determined by dividing horsepower actually used by velocity and the horsepower actually used is determined using the equation in Step 9.

Step 13. Compute maintenance, labor and parts requirements

De Weille's (4) table is used to obtain an estimated number of maintenance labor hours per 1000 kilometers and a parts requirement per 1000 kilometers expressed as a percent of original vehicle value. The factors are related to roadway surface type and vehicle velocity. Unfortunately, they are not related to the factors which determine vehicle velocity, including the roughness of the surface.

Step 14. Compute depreciation

For the depreciation calculation, de Weille's (4) tables are used. The tables do not relate depreciation to roughness of the surface,
curvature, rise and fall, or other factors which may affect the life of the vehicle. The ideal model would calculate depreciation as capitalized increases in future operating costs, especially future maintenance cost, as a function of the roadway design and condition. Unfortunately no such model exists.

It should be noted that depreciation is not equivalent to amortization. No interest on invested capital is included in this calculation. Interest is included in the cost per hour calculation in the following step.

**Step 15.** Compute economic and market vehicle time cost/km = Vehicle ($/hr)/vel.

This step is used to compute all costs which are fixed per unit time and not included elsewhere. In particular, it includes the opportunity cost of the capital invested in the vehicle. For example, ten percent per year on a $10,000 vehicle which operates 2000 hours per year is equivalent to $.50 per vehicle hour.

**Step 16.** Compute economic and market depreciation cost = (DEPR)(Vehicle Cost/1000)

DEPR factor taken from de Weille's table in Step 15

In this step depreciation cost per kilometer is determined using the vehicle original cost as the unit price.

**Step 17.** Compute economic and market maintenance cost

Labor Cost = LABOR* (MAINTENANCE LABOR WAGE/HR)/1000

LABOR = de Weille factor from Step 13

Parts Cost = PART* VEHICLE COST/1000

PART = de Weille factor calculated in Step 13

Maintenance cost per kilometer is determined using a wage rate for labor and the vehicle original cost for parts.

**Step 18.** Compute economic and market tire wear costs

TIRE COSTS = TIRE X ONE TIRE LIFE COST/1000

TIRE = de Weille factor calculated in Step 14

Tire costs per kilometer are computed from the cost of a tire life cycle, the original tire cost plus the cost of recapping it an average number of times.
Step 19. Compute economic and market driver and passenger cost:
\[
\text{Cost} = \frac{\left(\text{DRIVER WAGE/HR}/V\right) \times \text{CREW FACTOR}}{V}
\]
Driver and passenger labor cost per kilometer is determined by multiplying vehicle hours per kilometer by the number of people per vehicle and their wage rate.

Step 20. Compute economic and market cargo cost:
\[
\text{Cost} = \frac{\text{CARGO $/HR}}{V}
\]
Like the costs in Steps 16 and 19, this is a cost per vehicle hour. It would be used to assess a value of time savings for the shipment, but of course may be set to zero if not used in a given case.

Step 21. Are all subperiods simulated?
Yes, go to Step 23; No, go to Step 9, and increment subperiod index by one.

Step 22. Compute economic and market fuel costs:
\[
\text{Fuel} = \left(\text{Unit Cost Fuel $/liter}\right) \times \text{Fuel Consumed}
\]

Step 23. Compute total market cost:
\[
\text{Total Cost} = \text{time cost, depreciation, maintenance, tire, driver, cargo, fuel costs.}
\]

Step 24. Compute traffic volume:
\[
Q' = \left[-\varepsilon \left(P' - P\right)/P\right] \times Q + Q
\]
\[\varepsilon = \text{price elasticity of demand expressed as a positive number}\]
\[Q = \text{expected average daily traffic}\]
\[P = \text{cost per kilometer at which } N \text{ trips per day are expected}\]
\[P' = \text{total market cost per kilometer as computed in Step 23.}\]

The predicted traffic volume is computed using the total market cost per kilometer and a demand function which is described by a price, a quantity, and an elasticity.

Step 25. Compute loss of willingness-to-pay:
\[
\Delta W = \left(\frac{Q'}{2}\right)(P + P')/2
\]

The overall highway cost model is designed to compare the total cost of different roadway designs. In order to compare roads with more or less induced traffic, it is necessary to adjust costs for differences in benefits received. For example, an impassable road is the lowest cost in terms of the costs computed above but the trips not taken may be more valuable than the resources which are not required to produce them. Similarly, if user costs are very low, more trips may be taken with an associated...
increase in resources used but the increase in resource requirements is offset by the value of the extra trips. The value of the increased or decreased trips is expressed as the willingness-to-pay for the increment of trips. A reduction in willingness-to-pay is added to overall cost, while an increase which constitutes a benefit is subtracted from costs.

**Step 26.** Sum cargo costs, labor maintenance costs, and driver costs and multiply by the number of vehicles computed in 25 to arrive at a total labor cost.

**Step 27.** Sum tire cost and fuel cost and multiply by number of vehicles computed in Step 24 to arrive at a total materials cost.

**Step 28.** Sum depreciation cost, vehicle cost, and parts cost over all vehicles as computed in Step 24 to arrive at a total equipment cost.

**Step 29.** Are all vehicle types simulated?

- Yes, go to Step 31; No, go to Step 4 and increment vehicle index by 1.

**Step 30.** Multiply the labor costs, material costs, equipment cost and incremental willingness-to-pay by 365 to get an annual cost.
References


Chapter 5. Sensitivity Analysis

Sensitivity analysis was divided into two parts--1) an exploration of the sensitivity of cost to variation of selected parameters within the model, and 2) an exploration of the effect of design and maintenance policy variables on total cost. Only a few parameters and variables were selected for this analysis based on our a priori estimates of particularly important relationships. Selection of especially important relationships was the method chosen for sensitivity analysis since exhaustive exploration of all parameters and variables would have required more resources than were available.

Parameter Sensitivity

The first part of the analysis was conducted using data which describes a 10.8 kilometer roadway in St. Lucia, a small island in the Caribbean. The data were supplied by the World Bank and the Road Research Laboratory. The St. Lucia road crosses some rugged terrain and because of its relatively high design standards requires some large cuts and fills. The roadway rises from elevation 146.1 meters to elevation 260.4 meters in the first 3.3 kilometers and then falls to elevation 7.2 meters in the next 7.5 kilometers. A twenty year life of the roadway was simulated. The assumed traffic was a fleet of 80 horsepower autos weighing 800 kilograms and 65 horsepower trucks with 5000 kilogram gross weights. In the initial year the average daily traffic (ADT) consisted of 66 autos and 49 trucks. It was assumed that the traffic volume would grow at the rate of 10% per year almost independently of the highway design or maintenance policy.

The net present cost of a twenty year life of the roadway is shown in Table 5.1. This cost is divided into its three basic parts for two different designs--a paved road and a gravel road. In both cases construction cost is quite high because of the large amount of earthwork required for this particular road.

Table 5.1. Net Present Cost (8% Discount Rate) of St. Lucia Case over Twenty Years: Paved and Gravel.

<table>
<thead>
<tr>
<th></th>
<th>Paved</th>
<th>%</th>
<th>Gravel</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>319,000</td>
<td>78.6</td>
<td>258,953</td>
<td>68.7</td>
</tr>
<tr>
<td>Maintenance</td>
<td>5,655</td>
<td>1.4</td>
<td>2,860</td>
<td>0.8</td>
</tr>
<tr>
<td>Vehicle</td>
<td>80,735</td>
<td>20.0</td>
<td>114,268</td>
<td>30.5</td>
</tr>
<tr>
<td>Total</td>
<td>405,390</td>
<td>100.0</td>
<td>376,083</td>
<td>100.0</td>
</tr>
</tbody>
</table>

The primary purpose of the St. Lucia test runs were to determine how the base run costs in Table 5.1 would be changed by using different parameters or causal relationships within the model. Specifically, the
test runs focused on vehicle operating cost and the causal chain by which surface deterioration affects operating costs (Figure 5.1). Sensitivity runs demonstrate the consequence of errors in the following relationships.

1) Vehicle operation costs as a function of vehicle speed
2) Vehicle speed as a function of surface roughness
3) Surface roughness on gravel roads as a function of blading frequency, traffic, etc.
4) Surface roughness on paved roads as a function of initial design, traffic, etc.

Table 5.2 shows how a twenty percent variation in estimating vehicle speed would affect the twenty year cost estimates for St. Lucia. Note that this is a twenty percent error each year over the twenty year analysis horizon.

Table 5.2. Effect on Cost of Twenty Percent Speed Variation

<table>
<thead>
<tr>
<th></th>
<th>Base Cost</th>
<th>Speed 20% Above Base $</th>
<th>% of Base</th>
<th>Speed 20% Below Base $</th>
<th>% of Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>258,953</td>
<td>258,953</td>
<td>100</td>
<td>258,953</td>
<td>100</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2,860</td>
<td>2,860</td>
<td>100</td>
<td>2,860</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle</td>
<td>114,268</td>
<td>101,969</td>
<td>89</td>
<td>143,925</td>
<td>126</td>
</tr>
<tr>
<td>Total</td>
<td>376,081</td>
<td>363,782</td>
<td>97</td>
<td>405,738</td>
<td>108</td>
</tr>
</tbody>
</table>

For all years the vehicle velocity was limited by the roughness of the road surface. Because blading was specified at fixed time intervals and because average daily traffic increased ten percent per year, the road was rougher each year. With greater roughness each year, average velocities were lower each year. This effect is shown in Figure 5.2.

Because velocities were much lower in year twenty than in year one, it is also useful to look at vehicle operating cost comparisons in individual years as well as discounted over all twenty years. These are shown in Table 5.3. The slight deviation from monotonicity of the percentages is probably due to the use of discrete tables in the cost submodel.

Table 5.3 Effect of Vehicle Speed On Vehicle Operating Cost

<table>
<thead>
<tr>
<th>Year</th>
<th>Base Velocity km/hr</th>
<th>Market Cost of Vehicle Operations</th>
<th>Speed 20%</th>
<th>Speed 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Auto</td>
<td>Truck</td>
<td>Auto</td>
<td>Truck</td>
</tr>
<tr>
<td>1</td>
<td>66</td>
<td>49</td>
<td>0.028</td>
<td>0.219</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>37</td>
<td>0.03%</td>
<td>0.267</td>
</tr>
<tr>
<td>10</td>
<td>42</td>
<td>31</td>
<td>0.03%</td>
<td>0.303</td>
</tr>
<tr>
<td>15</td>
<td>28</td>
<td>20</td>
<td>0.044</td>
<td>0.422</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>6</td>
<td>0.093</td>
<td>1.218</td>
</tr>
</tbody>
</table>
Figure 5.1. Causal Chain Between Vehicle Operating Cost and Factors Affecting Roadway Surface Condition
Figure 5.2. Vehicle Velocities by Year - St. Lucia, Gravel Surface
In the St. Lucia, gravel road case, the factor which limited velocity in most years was surface roughness. Since the relationship between velocity and roughness was estimated from limited data, this relationship was the subject of two sensitivity runs. The results are shown in Table 5.4. In one run the velocity limit due to roughness was set 100 percent above the base run limit. For the other run it was set 50 percent below the limit in the base run.

Table 5.4. Sensitivity of Cost to Speed-Roughness Function

<table>
<thead>
<tr>
<th></th>
<th>Velocity Limit</th>
<th></th>
<th>Velocity Limit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base % of Base</td>
<td></td>
<td>Base % of Base</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>$258,953</td>
<td>100</td>
<td>$258,953</td>
<td>100</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$2,860</td>
<td>100</td>
<td>$2,860</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle</td>
<td>$114,268</td>
<td>61</td>
<td>$203,995</td>
<td>181</td>
</tr>
<tr>
<td>Total</td>
<td>$376,081</td>
<td>88</td>
<td>$465,808</td>
<td>124</td>
</tr>
</tbody>
</table>

There is also considerable uncertainty about how to accurately predict roughness. To determine the effect of incorrectly estimating roughness, two additional runs were made reflecting fifty percent variations in estimated roughness. The results are shown in Table 5.5.

Table 5.5. Effect of Variation in Estimated Roughness On Vehicle Operating Cost

<table>
<thead>
<tr>
<th></th>
<th>Roughness % of Base</th>
<th></th>
<th>Roughness % of Base</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% Above Base</td>
<td></td>
<td>50% Below Base</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>$258,953</td>
<td>100</td>
<td>$258,953</td>
<td>100</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$2,860</td>
<td>100</td>
<td>$2,860</td>
<td>100</td>
</tr>
<tr>
<td>Vehicle</td>
<td>$114,268</td>
<td>172</td>
<td>$63,563</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td>$376,081</td>
<td>122</td>
<td>$325,376</td>
<td>87</td>
</tr>
</tbody>
</table>

The final set of runs with the St. Lucia data was for a paved road. These runs show how costs depend on estimated rates of pavement deterioration. The results of a 50 percent increase in the deterioration rate and a 50 percent decrease in the deterioration rate are shown in Table 5.6. The effect was rather minor since serious deterioration did not occur until the last one to four years when the effect of annual operating costs on total net present costs is small. In other cases where traffic volumes are higher relative to the quality of construction the pavement deterioration relationship can be expected to have a much greater impact on total costs.
Design Variable Sensitivity

To illustrate using the model for determining how sensitive costs of a particular road may be to design variables, a tropical African case was used. The data for this case were provided by the World Bank from their files. The road is located in an area where plains merge into foothills so the terrain varies from flat to rolling. The rainfall in the area is about 90 centimeters per year. The soil has a California Bearing Ratio of 12 and is covered with light vegetation.

The proposed roadway designs included earth, gravel, and paved surfaces. The gravel surface initially would be 15 centimeters deep. The paved surface would consist of a 15 centimeter layer of cement treated aggregate plus a prime coat and a double bituminous surface treatment. All surfaces would be 5.5 meters wide with 1.5 meter shoulders.

Although data were furnished for a total length of 51 kilometers, most of the sensitivity runs were based on the 12 kilometer section designated as section 13 in the input forms. This section is in rolling terrain. Data necessary for the operation of the model, but not furnished by the Bank, were estimated by the study team to illustrate use of the model.

Vehicle data were provided by the team using the vehicle description in de Weille's Quantification of Road User Savings. Principal characteristics of these vehicles are shown in Table 5.7.

Table 5.7. Vehicle Characteristics

<table>
<thead>
<tr>
<th>Gross Vehicle</th>
<th>Weight</th>
<th>H.P.</th>
<th># of Tires</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Car</td>
<td>840 kgs</td>
<td>40</td>
<td>4</td>
<td>$1,590</td>
</tr>
<tr>
<td>Light Truck</td>
<td>2,700 kgs</td>
<td>140</td>
<td>4</td>
<td>$2,500</td>
</tr>
<tr>
<td>Heavy Truck</td>
<td>26,000 kgs</td>
<td>210</td>
<td>14</td>
<td>$11,800</td>
</tr>
</tbody>
</table>
This typical run describes a 12 kilometer section of gravel road with a maximum grade of 8% and an average rate of rise and fall of one foot per hundred. Average daily traffic was about 50 vehicles. The specific traffic flow is shown in Table 5.8. The road was bladed after every 5,000 vehicles or approximately every three months.

Table 5.8. Average Daily Traffic for Typical Run

<table>
<thead>
<tr>
<th>Year</th>
<th>European Car</th>
<th>Light Truck</th>
<th>Heavy Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>

For this tropical African case one of the policy variables was the frequency of blading gravel roads. Table 5.9 shows the consequence of alternative blading frequencies. From these runs it appears that the optimal blading frequency is about once every 5,000 vehicles. Less frequent blading increased vehicle operating costs more than it decreases maintenance costs while the converse is true for more frequent blading.

Table 5.9. Equivalent Annual Maintenance and Vehicle Costs for Alternative Maintenance Policies on Gravel Roads

<table>
<thead>
<tr>
<th>Maintenance Level</th>
<th>Annual Maintenance Cost</th>
<th>Annual Vehicle Cost</th>
<th>Annual Maintenance and Vehicle Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent Maintenance</td>
<td>1,050</td>
<td>3,980</td>
<td>5,030</td>
</tr>
<tr>
<td>(Blade every 2,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good Maintenance</td>
<td>490</td>
<td>4,060</td>
<td>4,550</td>
</tr>
<tr>
<td>(Blade every 5,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor Maintenance</td>
<td>273</td>
<td>4,630</td>
<td>4,903</td>
</tr>
<tr>
<td>(Blade after 12,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.10 shows a similar result for earth road maintenance. Here, however, we find that the consequence of poor maintenance is much more pronounced. Here a reduction of less than $200 per year on maintenance results in nearly $4,000 per year increase in operating costs.
Table 5.10. Equivalent Annual Maintenance and Vehicle Costs for Alternative Maintenance Policies on Earth Roads

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent Maintenance</td>
<td>870</td>
<td>6,350</td>
<td>7,230</td>
</tr>
<tr>
<td>(Blade every 2,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good Maintenance</td>
<td>400</td>
<td>6,450</td>
<td>6,850</td>
</tr>
<tr>
<td>(Blade every 5,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor Maintenance</td>
<td>220</td>
<td>10,400</td>
<td>10,620</td>
</tr>
<tr>
<td>(Blade every 12,000 vehicles)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity to Profile Changes

Costs are sensitive to roadway profile as well as to the type and condition of the surface. An increased rate of rise and fall increases vehicle operating costs by reducing vehicle speed and by increasing fuel consumption. The effects are illustrated graphically in Figures 5.3 through 5.6.

Figure 5.3 shows how increasing rise and fall reduces vehicle velocity. Here the effect is shown for a heavy truck with low horsepower to weight ratio. Higher powered vehicles would be less affected by increased rise and fall.

Figures 5.4 and 5.5 show how the profile affects fuel consumption. Figure 5.4 shows the effect of changing a long continuous grade. In this case fuel consumption increases monotonically with increasing grade. However, on rolling terrain, as shown in Figure 5.5, a slightly rolling terrain requires less fuel than level terrain. This is because the engine can operate at near peak efficiency without losing momentum.

Both fuel consumption and vehicle velocity influence total vehicle operating cost. This combined effect for the fleet described in Table 5.7 is shown in Figure 5.6.
Figure 5.3. The Effect of Rise and Fall on Velocity--Heavy Truck on Paved Surface.

Figure 5.4. The Effect of Continuous Adverse Grade--Gravel, Earth, Paved--On Miles per Gallon--European Car.
Figure 5.5. The Effect of Rise and Fall on Miles per Gallon - Light Truck on Paved Surface.

Figure 5.6. The Effect of Rise and Fall on Average Annual Total Fleet Operating Costs.
Chapter 6. Conclusions and Recommendations

A prototype highway system cost simulation model has been developed. The model is operational and has been tested using realistic data provided by the Bank. We believe the model is sufficiently complete and accurate to be a useful aid in preliminary feasibility analysis of road projects, but we do not suggest that it can be used without considerable engineering judgment and knowledge of local condition. It would be a supplement to rather than a replacement for conventional procedures of feasibility studies.

We recommend that this model be used in the preliminary design of a small number of highway projects so that its effectiveness can be evaluated and its most significant shortcomings clearly identified. The first applications of the model should be undertaken in the spirit of an extension of the phase I research.

In addition to the general recommendation that the model be used by experienced engineers, the following specific recommendations are offered. They are divided into two parts -- Model modifications and empirical work to improve the estimate of model parameters. These recommendations are based on the entire model building and testing experience. The sensitivity runs discussed in Chapter 5 were especially useful in developing some of these recommendations.

We conclude that user costs are likely to be a major element even when major earthwork cost is incurred as in St. Lucia. Hence we suggest that much of the second phase work be addressed to improving the accuracy of the relationships which determine vehicle operating cost. In particular, it appears that surface roughness has a major impact on vehicle operating costs. Consequently many of the surface roughness relationships should be studied further.

The following recommendations for empirical work are divided into three parts:

a. Vehicle Operations Submodel
b. Maintenance Submodel
c. Construction Submodel

**Vehicle Operations**

1. Surface roughness has a major impact on vehicle costs but the relationship between cost and roughness is inadequate. The effect of roughness on vehicle velocity could be more accurately determined with some relatively inexpensive field work. The effect on fuel consumption and vehicle wear will be more difficult to determine but it should be attempted. In the present model, the only effect is through speed -- increased roughness leads to lower speed which leads to lower fuel and maintenance costs.
costs although this is partially offset by crew, depreciation, and other time dependent costs. In fact, greater resistance of the rough road should increase fuel consumed at any given speed and the increased shock and vibration should increase vehicle and tire wear.

2. The relationship between vehicle speed and roughness is based on a limited data set. More data, especially for very rough roads should be collected and the relationship reestimated.

3. The effect of vertical profile on velocity and fuel consumption is based on truck operations data collected in 1948. The form of these models is believed to be quite satisfactory but it would be useful to recalibrate the models for a wider range of vehicle and roadway types. This could be done at modest cost. The fuel consumption model should also reflect the lower fuel requirement when velocity is limited by something other than available horsepower. Separate calibrations for diesel would also be useful.

4. The effect of horizontal alignment on velocity and operating cost is, at present, represented by a conventional "law of physics" formula. The formula does not take into account different coefficients of friction for different vehicle types. Neither does it directly account for different acceleration and deceleration possibilities with different vehicles. It is possible that field work would permit the creation of a more accurate relationship. It may also be possible to measure the effects of curvature on fuel consumption as influenced by acceleration and deceleration in a carefully designed field study. At present this can only be done by very detailed simulation models such as the one in ICES ROADS.

5. The present model does not include any relationships for predicting which vehicles will find an earth road impassable nor does it compute a cost or loss of consumer surplus due to impassable roads. The conceptual framework but not the data exist for incorporating this in the model.

Maintenance

1. Asphalt surface deterioration rates are based on the AASHO Road Test results. Attempts should be made -- through a controlled field experiment or collection of field data -- to verify the relationship between Present Serviceability Index (as developed by AASHO) and the physical measures of deterioration that affect maintenance demand. These are now based on the regression analysis done during this study and during the AASHO Road Test. However, the data from these analyses were from a limited geographical area, and do not contain observations on extremely rough roads. Also the relationships between PSI and roughness for very rough paved roads should be reexamined.
2. The effect of maintenance action on the physical measures of deterioration and on PSI should be measured for a variety of maintenance procedures. The study should be carried out over a period of several years so that the long term as well as the short term effects of maintenance can be observed.

3. Attempt should be made to identify the factors affecting the roughness of gravel surfaces. Vehicle weight, speed, and configurations, gravel type and gradation, rainfall, subsoil, and type of maintenance have all been suggested as contributing factors. It may be possible to obtain data on some of these by observation of existing roads. For example, the effect of vehicle speed might be determined by a program of roughness measurement on tangent sections of the same road where the same stream of vehicles travel at different speeds because of speed limits, approaching curves, or other factors. Similarly, the effect of vehicle weight might be examined by using similar sections of road which have different traffic compositions.

4. Study should be made of the effect of various procedures for blading and dragging on roughness of gravel roads. This may be possible at relatively low cost by observing the roughness of roads in maintenance districts which use two or more methods of smoothing gravel surfaces. If the model is to be used in developing countries, some of the labor intensive methods of dragging or brooming the surface should be studied.

5. Studies of the types suggested in 3 and 4 should also be made for earth surfaces.

6. Drainage maintenance and vegetation control have no effect on the deterioration rate of the roadway surface in the current model. However, if little or no maintenance is planned or expected for these items, surface deterioration is probably accelerated and the model should have the capability of representing this relationship. This will probably be an easy relationship to determine. The priority of research to determine this relationship will depend on how often the Bank expects these two maintenance operations to be neglected on the projects of interest.

**Construction**

1. Drainage. The drainage component of the construction submodel must be reexamined if the model is to be used to predict the consequences of inadequate maintenance in areas where drainage is important. The present model estimates the number and size
of culverts needed for good drainage but it does not predict the consequences of installing fewer or smaller culverts. It is based on separate research by Lago and McCoomb and may not be directly applicable to tropical areas.

2. Earthwork. a) The use of the rate of rise and fall of the terrain and maximum grade of the profile as a basis for estimating earthwork quantities represents a new approach and as such should be used with some care. The methodology was developed on a somewhat limited data base and with an orientation towards very high design standard roadways.

   i) The transferability of results from high design standard to low design roadways has not yet been fully demonstrated. Profile grades for the different design standards and resulting earthwork volumes may be considerably different, particularly in rough topography.

   ii) The data were obtained using a one point level cross-section, ignoring the effects of ground cross-slope, and will tend to underestimate volumes.

   iii) The original data were plotted based on 10 mile section lengths. Since the resultant curves were non-linear, care should be exercised in using segment lengths other than 10 miles.

   iv) Effects of such geologic conditions as rock and unsuitable material were not taken into consideration.

   v) Profile lines were based on a balance of excavation and embankment quantities. In many cases, this is not normal design practice and an excess of excavation is planned.

Even though these limitations exist, the basic simplicity of the model makes it worth retaining in the highway cost model. It can be used during preliminary design stages when only low scale mapping is available. Similarly, the one-point model can be used when more detailed design inputs are not available or design systems such as ICES ROADS may be used when field survey data is available. Testing the accuracy of the three approaches with field data would facilitate selection of an approach for a specific problem.

b) Both earthwork submodels now require a quantitative terrain descriptor. In the early planning phases of a study, many engineering organizations prefer to work with a qualitative description or classification scheme of the topography based
analysis of aerial photographs. The addition of a third and qualitative terrain model would be useful.

c) Both the one-point elevation and contour line density terrain models assume a level cross-section. As noted above, however, the cross-slope of the terrain is a primary determinant of the earthwork volumes associated with construction of low cost roads, particularly in mountainous or rugged terrain. Techniques of incorporating the terrain cross-slope into the current one-point models could be developed.

In addition to the primarily empirical work suggested in the preceding section, some suggestions are also offered for modification and use of the model. The suggestions follow:

Vehicle Operations

As mentioned in the preceding section, the model could incorporate a calculation of value lost due to impassable roads. This requires empirical work plus minor modifications in the vehicle submodel.

Maintenance

1. The assumed productivity factors for various maintenance operations now in the model are based on the most accurate information that could be assembled. However, only a small portion of this information originated in developing countries. Productivity factors should be determined for typical situations in developing countries. This is especially important for the assumption of actual time worked per hour, which is used in the model as a general efficiency measure. This factor, when known, can be used to calibrate the maintenance cost model for the overall efficiency of the maintenance organization.

2. The effectiveness of dragging rather than blading should be established and the appropriate adjustments made in the model before this model is used to evaluate roads in regions where dragging is the predominant form of surface maintenance.

3. The capability of predicting the fraction of the year which earth roads are impassable could be developed and included in the model. This would eliminate the need for the model user making this prediction before running the model.
Construction

1. Construction related technology and productivity data may be available in a variety of forms including unit costs, productivity and costs of aggregated equipment and labor packages as are now input to the model, and productivities and costs of individual units of equipment and labor in a disaggregated form. The construction submodel could allow input of technology and productivity data in a variety of forms.

2. The pavement submodel is oriented to the three basic pavement types of earth, gravel, and asphalt. Extensions could be made to facilitate the description and handling of additional pavement types such as represented by surface stabilization with asphalt emulsions, salts, or other means.

3. The current construction model does not explicitly treat structures, yet the trade-off between earthwork and structural requirements can be important. The feasibility of extending the basic model to include a structural component should be investigated.

Computer System Improvements

1. The current model was developed for a batch mode of computer usage. A more natural and efficient way of using the model to explore design issues is in an interactive computer environment. Time sharing or remote job entry versions would both be improved forms of the basic model.

2. Currently, all data must be input for each computer run. Basic data should be stored on secondary storage so that they need not be re-input. Data modification capabilities could be introduced.

3. Only tabular output reports are now generated. Graphical output could also be produced. For example, the time stream of the construction, maintenance, and operating costs could be plotted.

4. It would be desirable to save user selected cost and quantity information between runs so that a variety of tabular and graphical summary reports could be automatically generated to compare different designs. For example, trade-off curves and sensitivity plots could be automatically drawn on a digital line plotter.

5. Greater selectivity of output reports could be provided to a user of the model. For example, only selected physical quantities and costs could be printed during a run if a particular design trade-off was being investigated.
6. The current data and program structure were designed to facilitate the development of an operational prototype model. Changes could be made to improve the operation and usage of the model under production conditions.

7. All data are input from fixed format input forms. While this form is useful for this type of problem, the addition of optional engineering oriented input language and flexible data forms could significantly improve the flexibility and usability of the model.
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<th>Page</th>
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</thead>
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</tr>
<tr>
<td>Bituminous Surface Maintenance</td>
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<td>General</td>
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<td>Tractor and Mower</td>
<td>A-17</td>
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</table>
Appendix A

This appendix contains the basic assumptions upon which the current maintenance model is based. These assumptions were made on the basis of the author's experience and information found during the review of literature. As a result, the assumptions are felt to be realistic given the time allowed for the study. However, if the model user has additional information available as a result of either local experience or research done subsequent to this study, it can be used to upgrade the model by modifying the appropriate model constants.

The following page contains a table of contents giving the pages on which the specific assumptions for a particular model component are described.
ASSUMPTIONS FOR BITUMINOUS SURFACE MAINTENANCE

I. General

1. The deterioration in a paved surface during any year of the analysis period can be predicted as a function of:
   a. condition of surface at start of year
   b. initial quality of the pavement design (as measured by a structural number)
   c. quality of subgrade soil (as measured by CBR)
   d. age of surface (since construction or last resurfacing)
   e. volume and weight of traffic using surface for year
   f. maintenance performed during year.

2. Deterioration is defined for this study by changes in the parameters of PSI and coefficient of traction.

3. Most important aspects of deterioration are incorporated in the concept of the AASHO present serviceability index (PSI) as found by:

   \[ \text{PSI} = 5.03 - 1.91 \log (1 + \overline{SV}) - 0.01 \sqrt{C + P} - 1.38RD^2 \]  

where:

   \( \overline{SV} \) = the mean slope variance in wheel paths

   \( (C + P) \) = the area of surface that is either cracked or patched (expressed in m²/1000m²)

   \( RD \) = the mean rut depth in the wheel paths.

4. The coefficient of traction for wet pavement is initially 0.6 (IFRCW = 0.6). This decreases due to bleeding and aggregate polishing to a minimum of 0.3 (FFRCW = 0.3) in about ten years after construction or resurfacing (DFRC = 0.03). (3, 4)

*Numbers in parentheses refer to references at the end of this appendix.
GENERAL MODEL ASSUMPTIONS

1. Unit cost of equipment time includes allowance for all depreciation, repair, maintenance, and tire or track wear; but does not include cost of fuel or operator.

2. A common size is assumed for each type of equipment in cost predicting subroutines. The actual use of equipment somewhat smaller or larger than this assumed size is not expected to significantly affect accuracy since the changes in productivity and unit cost tend to cancel each other.

3. All maintenance operation can be done without significant interference with traffic.

4. Ratio of net working time to total working time for labor = 45 min/hr (PCL = 0.75).
2. All costs for preparing and storing the premixed patching material are included in a "price" for the material at the central location. The cost of obtaining the material on the road section of interest is thus dependent only on this source "price" and the cost of transportation.

3. The trucks used to haul the material to the actual patching site are also used to roll the completed patching. As a result, trucks are the only type of equipment used in addition to hand tools.

4. Average thickness of all patches placed (both skin patches and deep patches) is 5cm (DOP = 5).

5. Placing and rolling cold mix for deep patches or skin patches requires the following expenditure of labor and equipment per cubic meter: (7, 8, 9)
   a. 7.0 hours of common labor (CCM1 = 7.0)
   b. 3.0 hours of dump truck and driver (CCM2 = 3.0)

6. The cost of transporting cold mix from a source to the road section can be found using the same estimates of productivity and consumption used for transporting gravel.

7. The percent of liquid asphalt used in the cold mix is 6% of the aggregate weight (AC = 0.06).

8. The mean slope variance (SV) is partially made up of depressions and potholes which are likely to be repaired by patching. Therefore, patching reduces the mean slope variance and this reduction (FIXSV) is a function of the fraction to be patched and the slope variance. The reduction for each year is estimated to be:

   \[ \text{FIXSV} = 0.3 \text{(FTP)}(SV)(KK) \]

   (FIXSV varies between 0 and 1.0)

where KK is an adjustment factor that varies with the amount of cracking that appears each year. That is, the more patching that is done, the more SV will be affected.

III Assumptions Concerning Sealing

1. Assume that the source of aggregate for sealing is the same as the source of bituminous cold mix.

2. The cost of transporting the aggregate from the source to the road section can be found using the same estimates for productivity and consumption used for transporting gravel.

3. The costs of transporting the liquid asphalt are absorbed in the costs of the distributor and are not explicitly calculated.
5. A wet surface is assumed for that fraction of the year input as IMPS.

6. The coefficient of traction for dry pavement surface is constant and equal to 0.7 for the life of the surface. (4)

7. Rolling resistance on paved surfaces is constant at 0.01 for all conditions and ages of interest. (5)

8. Once PSI has been computed, mean slope variance ($SV$) can be estimated from the relationship:

$$SV = \left[ 0.031PSI^2 - 6.5PSI + 27 \right] - 1.0 \quad R^2=.91$$

This equation is based on correlation studies made during the AASHO Road Test. (2)

9. Roughness ($RUF$) is well correlated with AASHO serviceability ($PSI$), and the relationship can be expressed as:

$$Roughness = (5.0 - PSI)/.015 \quad R^2=.89$$

10. The area of cracking and patching ($C&P$) can be estimated by the relationship:

$$C + P = \begin{cases} 0 & \text{if } PSI \geq 4.3 \\ (0.3PSI^3 - 1.3PSI^2 - 6.2PSI + 29)^2 & \text{if } PSI < 4.3 \end{cases} \quad R^2=.68$$

This equation is based on correlation studies made during the AASHO Road Test. (2)

11. The mean rut depth ($RD$) can be estimated for any level of serviceability by the relationship:

$$RD = -0.03PSI^2 = 0.091PSI = 0.32 \quad R^2=.61$$

From AASHO Road Test. (2)

12. If resurfacing is called for, it is handled as a reconstruction operation; therefore, the maintenance model doesn't predict cost of resurfacing.

I. For equations 8, 10, and 11, the regression equations were found using data from the AASHO Road Test utilizing the IBM Scientific Subroutine Package routine POLRG. For equation 9, the regression coefficients were found by Yoder and Milhous and reported in N.C.H.R.P. Report #7, Highway Research Board, 1964.

II. Assumptions Concerning Patching

1. All patching is done with bituminous cold mix that is obtained by the local maintenance crews from a central location.
6. Since only the deeper ruts will be filled, the average rut depth will be reduced each time ruts are repaired.

7. Assume that the depth of ruts are normally distributed. For this distribution the reduction in mean rut depth (\(\text{FIXRD}\)) will be approximately one-half of fraction of ruts filled (\(\text{FRF}\)).

\[
\text{FIXRD} = 0.5 \times (\text{FRF})(\text{RD}).
\]

8. Assume that the shape and size of the average rut filled will be as follows:

Note: This assumption should be valid for values of \(\text{FRF}\) between 10 and 30 percent.

Volume of patching material required for one kilometer of roadway

\[
\text{(CMPR)} = \frac{4 \times \text{FRF} \times 1.6 \times \text{RD} \times 0.8 \times 1000 \text{m}}{100 \text{ cm/m}} = 50 \times \text{FRF} \times \text{RD}
\]
4. Aggregate is applied at rate of 14 kilo/m\(^2\). \((SA = 14)\)

5. Bitumen is applied at rate of 1.2 liters/m\(^2\). \((SB = 1.2)\)

6. Sealing 100 square meters required the following expenditure of labor and equipment: \((7, 8, 9)\)
   - 1.4 hours of common labor \((CS1 = 1.4)\)
   - 1.4 hours of truck and driver \((CS2 = 1.4)\)
   - 0.4 hours of distributor and operator \((CS3 = 0.4)\)
   - 0.3 hours of roller and operator \((CS4 = 0.3)\)

7. Costs for small items such as spreader attachments for trucks, brooms, rakes, etc., are not explicitly calculated but are considered as part of the cost of related equipment.

8. Sealing the surface reduces the amount of cracking and patching noticeable on the road surface. This reduction \((\text{FIXCP})\) is a function of area sealed each year \([\text{FTS} \times \Delta(C + P)]\). The amount of reduction for each year (in square meters) is estimated to be:

   \[
   \text{FIXCP} = (0.5)(\text{FTS})\Delta(C + P).
   \]

### IV Assumptions Concerning Rut Repair

1. All patching is done with bituminous cold mix that is obtained by the local maintenance crews from a central location.

2. All costs for preparing and storing the premixed patching material are included in a "price for the material at the central location". The cost of obtaining the material on the road of interest is thus dependent only on this source "price" and the cost of transportation.

3. The cost of transporting cold mix from a source to the road section can be found using the same estimates of productivity and consumption used for transporting gravel.

4. The percent of liquid asphalt used in the cold mix is 6% of the aggregate weight. \((AC = 0.06)\).

5. This operation is assumed to be mechanized with a motor grader spreading the material. Placing and compacting patching material for rut repair requires the following expenditures of labor and equipment per cubic meter: \((7, 8, 9)\)
II. Assumptions Concerning Blading

1. The surface can be bladed with two passes/area of the grader over the area to be bladed (Pass 1 = 2) (11).

2. The surface is bladed on a selected schedule year-round by adding water during the dry season.

3. Except during dry season, traffic compacts the surface satisfactorily after blading and no additional compaction need be provided.

4. During the dry season, the top 5 cm (AG1=5) of gravel must have its moisture raised 4% (WA1=.04) to allow effective compaction.

5. When water must be added it is assumed that a roller is needed to compact the bladed and watered material since it is likely to dry before it can be compacted by traffic.

III Assumptions Concerning Regravelling

1. Regravelling is done when gravel thickness is reduced to 10 centimeters (TCRC = 10).

2. Existing surface is bladed to a depth of 3 cm (BD = 3) to remove corrugations.

3. A quantity of gravel, equivalent to 5cm of compacted depth, is added (AG2=5).

4. Loose gravel - both original and new - must have moisture raised 4% (WA2=.04).

5. All required water can be applied in two passes.

6. Four grader passes per area are necessary for regravelling.

7. Assume that the gravel replacement operation will be organized (truck to loader ratio, etc.) so that each truck round trip requires 6 min. of loader time (5 min. to actually load and 1 min. of delay). Thus the loader can load 10 trucks each hour of net working time.
ASSUMPTIONS FOR GRAVEL ROAD MAINTENANCE

I. General

1. Average roughness (within attainable range of gravel road) is dependent only on maintenance policy and traffic load.

2. Rolling resistance and coefficient of traction is dependent only on maintenance policy and traffic load except during periods of prolonged heavy rainfall when road becomes spongy and somewhat slicker.

3. As a result of the first two assumptions, output to user cost model will be in the form of one roughness value for each year if blading frequency is the same for wet and dry seasons. Two roughness values will be computed if the blading frequency is different for wet and dry seasons. Three levels of rolling resistance and coefficient of traction will be output each year; one for dry season, one for wet season and one for in-between.

5. All maintenance operations can be done without significantly interfering with traffic.

6. One cubic meter of compacted gravel weighs 2240 kilograms (DCG=2.24).

7. One cubic meter of loose gravel weighs 1800 kilograms (DLG=1.8).
ASSUMPTIONS FOR EARTH ROAD MAINTENANCE

I. General Assumptions

1. Average roughness (within range attainable on earth surface) is dependent only on maintenance policy and traffic load.

2. Rolling resistance (RR) and coefficient of traction (CT) is also dependent on maintenance policy and traffic load, but rainfall and soil type have an additional effect.

3. RR and CT vary over a wide range during the year but it is assumed that this variation can be adequately represented by considering three distinct levels: dry surface, wet surface and softened surface.

4. Water must be added for effective blading during the fraction of the year input as "DRY".

5. An impassable surface is assumed for that fraction of the year input as "IMPS".

6. A slightly softened surface is assumed for that fraction of the year not included in either DRY or IMPS (rolling resistance is somewhat higher.)

II. Assumptions Concerning Blading

1. The surface is bladed on a selected schedule year-round by adding water during the dry season.

2. Except during the dry season (DRY) traffic compacts the surface satisfactorily after blading and no additional compaction is provided.

3. During the dry season (DRY) the top 5 cm (AE=5) of soil must have its moisture raised 2% (WA3=02) to allow effective compaction.

4. When water must be added, it is assumed that the material must be rolled to prevent drying out before compaction.

ASSUMPTIONS FOR DRAINAGE MAINTENANCE

1. Basic measure of work is cubic meters of soil that is removed from ditches and drainage structures.
8. Assume that amount of gravel lost from surface is directly proportional to the total weight of vehicles using road. The number of each type of vehicle will be converted to an equivalent number of 1600 kilogram vehicles. The total number of equivalent vehicles will be used to estimate gravel loss. This assumption appears to explain the difference in gravel loss rate between the two most complete reports concerning gravel loss. (8, 18)

9. Assume that 0.9 metric tons of gravel is lost per year per kilometer for each 365 equivalent vehicles (one per day) that uses the road. (GL = .9) (8,10,13)
4. The patching and rut filling needed for bituminous shoulders increases by 50% (SBI = .5) for each meter that the roadway surface is less than 7 meters. (17) (i.e., A 6 meter wide road will require 50% more shoulder maintenance than one 7 meters and a 5 meter road will require 50% more than a 6 meter road.)

5. Bituminous shoulders for a 7 meter wide travelled surface require 10% as much patching and rut filling per area as the travelled surface. (7)

ASSUMPTIONS FOR GRAVEL SHOULDER MAINTENANCE

1. Shoulder maintenance is a minor fraction of the total maintenance cost. (8,18) Therefore, typical maintenance policy will be assumed instead of complicating the model by asking the model user to specify policy.

2. The shoulders are bladed at least once per year.

3. The shoulders are bladed an additional time for each 500 vehicles per day (ADT) above 500 ADT. (FREQF = 500). (16)

4. The number of needed shoulder bladings is greater for narrow roadways. It is assumed that the need for bladings increases 50% (SGI = .5) for each meter that the roadway surface is less than 7 meters. (17)

5. One shoulder blading requires 2 passes of the motor-grader. (9) (4 passes for both shoulders)

6. Shoulder blading can be scheduled to be done when surface is damp and therefore no water need be added. That is, the model assumes surface is damp and therefore no water need be added.

7. Bladed shoulder material must be rolled since it is not likely to be compacted by traffic. (19)

8. Shoulder can be satisfactorily compacted with same number of passes as for compacting bladed gravel road (RP4) and the width which needs to be rolled is not wider than roller. Therefore, passes needed to roll one section of road (both shoulders) = 2 x PR4.
2. All work is done with a standard crew of 25 laborers, 4 trucks and one motorgrader. The assumed operation uses the motorgrader to grade the ditches to their original depth. The laborers load the soil into trucks for removal and do whatever hand work is necessary to clean out and repair the drainage structures within the work area.

3. This crew is capable of removing 100 cubic meters of sediment from the drainage ditches in one day (6 hours working time and a ratio of working time to total time of 3:4 (PCL=.75). (7,8,9,14)

4. The relative amounts of sediment deposited in the drainage system can be estimated by the following relationship:

\[
\text{sediment (in cubic meters)} = 6 + 3 \times [(1 + RF/100)TFSSF]
\]

where:

RF = annual rainfall in centimeters (15)
TF = adjustment factor for terrain (8)

a. mountainous = 1.0
b. rolling = 2.0
c. flat = 3.0

SSF = adjustment factor for side slopes =
\[
\frac{1}{\text{cut slope}} + \frac{1}{\text{fill slope}} + 0.5
\]

ASSUMPTIONS FOR MAINTENANCE OF BITUMINOUS SHOULDERS

1. Shoulder maintenance is a minor fraction of the total maintenance cost. Therefore a typical maintenance policy will be assumed instead of asking the model user to specify a policy.

2. The shoulders are sealed a minimum of once every ten years (0.1 of shoulder area is sealed each year.) (9)

3. The most common repair needed will probably be filling the depressions that form the edge of the travelled surface. The repair needed for this deterioration is considered to be proportional to the patching and rut filling needed for the travelled surface since they are both affected by the traffic volume, subsoil quality, and climate. (16)
Consumption

a. fuel consumption = 5 liters (gasoline)/hr
b. operator time = 1.0 hrs/total working hrs

CR1 = 5
CR2 = 1.0

3. Water Truck (6 cubic meter truck with pump)

Production

a. capacity = 6.0 cubic meters
b. ratio of net-to-total work time = 45 min/hr
c. average haul speed = 40

d. average spray speed = 10 kilometer/hr
e. loading and delay time = 20 min/round trip
f. width of sprayed area = 4 meters
g. passes needed to apply water = 2

PWT1 = 6.0
PWT2 = 0.75
PWT3 = 40
PWT4 = 10
PWT5 = 20
PWT6 = 4.0
PWT7 = 2

Consumption

a. fuel consumption = 9 liters (gasoline)/total hrs
b. driver time = 1.0 hrs/total working time

CWT1 = 9
CWT2 = 1.0

4. Dump Truck (3 cubic meters)

Production

a. capacity = 3 cubic meters
b. ratio of net-to-total working time = 45 min/hr
c. haul speed = 40 kilometers/hr
d. time to load (during regraveling) = 5 min
e. time to unload (gravel) = 2 minutes
f. delay time per round trip (regraveling) = 5 minutes

PT1 = 3.0
PT2 = 0.75
PT3 = 40
PT4 = 5
PT5 = 2
PT6 = 5
DETAILED ASSUMPTIONS OF EQUIPMENT PRODUCTIVITY AND CONSUMPTION

1. Motor Grader (3.7 meter blade)

Production
   a. coverage = 2.4 meter/pass  \( PMG_1 = 2.4 \)
   b. ratio of net working time to total working time = 45 min/hr  \( PMG_2 = 0.75 \)
   c. working travel speed = 6.0 kilometer/hr  \( PMG_3 = 6.0 \)

Consumption
   a. fuel consumption = 15 liter (diesel)/total hours  \( CMG_1 = 15.0 \)
   b. operator time = 1.0 hours/total work hours  \( CMG_2 = 1.0 \)

2. Roller (10-ton, self-propelled)

Production
   a. coverage = 2 meters  \( PRI = 2 \)
   b. ratio of net-to-total work time = 45 min/hr  \( PR_2 = 0.75 \)
   c. work travel speed = 6.0 kilometer/hr  \( PR_3 = 6.0 \)
   d. 3 passes will compact 6 cm of loose material  \( PR_4 = 3 \)
   e. 5 passes will compact 10 cm of loose material  \( PR_5 = 5 \)
c. working travel speed = 5 kilometers/hour  PV3 = 5.0

Consumption

a. fuel consumption = 4 liters/kilometer  CV1 = 4.0
b. driving time = 1.0 hour/total work hour  CV2 = 1.0
Consumption

a. fuel consumption = 7 liters (gasoline)/hr   CT1 = 7
b. driver time = 1.0 hrs/total working time   CT2 = 1.0

5. Loader (1 cubic meter capacity)

Production

a. production rate (regravelling operation) = 30 m$^3$ (10 trucks) per hour/working time   PL1 = 30
b. ratio of net-to-total working time = 45 min/hr   PL2 = 0.75

Consumption

a. fuel consumption = 12 liter (gasoline)/hr   CL1 = 12
b. operator time = 1.0 hrs/total work hours   CL2 = 1.0

6. Bituminous Distributor

Production

a. capacity = 5M$^3$   PD1 = 5
b. ratio of net to total working time = 45 min/hr   PD2 = 0.75

Consumption

a. fuel consumption (gasoline) = 7 liters/hr   CD1 = 7
b. driver time = 1.0 hours/total work hour   CD2 = 1.0

7. Tractor and Mower (1.8 meter mower)

Production

a. capacity = 1.8 meter per pass   PV1 = 1.8
b. ratio of net working time to total working time = 45 min/hr   PV2 = 0.75

13 Millard, R.S., "Road Transport Costs in Developing Countries," Road International, No. 53, June 1964.


REFERENCES

1. **analysis horizon** - span of time selected by analyst during which all costs and benefits are considered in an economic analysis.

2. **equilibrium velocity model** - a vehicle simulation model which determines the equilibrium speed of a vehicle as a function of the factors that affect that speed.

3. **rolling resistance** - resistance to vehicle travel as a result of the frictional losses in the tires and travel surface.

4. **air resistance** - resistance to vehicle travel generated by the frictional losses in air due to vehicle movement.

5. **PSI - (AASHO Present Serviceability Index)**
   \[
   \text{PSI} = 5.03 - 191 \log (1 + SV) - 0.01 C + P - 1.38 RD^2
   \]
   where SV, C + P, and RD are as defined below.

6. **SV - slope variance** - the variance (mean square deviation) of a set of slopes about the mean longitudinal slope in the wheel path (mean slope variance, SV, is the mean of the two wheel paths).

7. **RD - rut depth** - the maximum vertical displacement of a point of the surface measured from the center of a 4 foot transverse straight-edge.

8. **C + P - cracking plus patching** - area of cracking and patching on paved surface (square meters per 1000 square meters).

9. **vertical profile** - two-dimensional description of vertical location of centerline of road relative to longitudinal distance along road.

10. **horizontal alignment** - description of the horizontal variation of roadway centerline (directions, curves, etc.)

11. **earthwork borrow** - quantity of earthwork needed to complete roadway after all cut sections are complete; this must be obtained from excavation sites outside of the road proper.

12. **road template** - two-dimensional diagram which defines the desired transverse cross-section of the roadway (surface, shoulders, ditches, slopes, etc.)