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A description of an analytic model--the Highway Cost Model--for use in evaluating alternative design and maintenance strategies for low-volume roads. The focus of the model is on project-level engineering decisions and their implications for total transport costs. The types of decisions which are within the scope of the model include the choice of alignment, geometric standard, surface type, maintenance policy, and construction and maintenance methods. The costs considered include construction, maintenance, and road user costs, all of which are estimated in terms of the labor, equipment, and material resources required. The model may be used at both the pre-feasibility and feasibility stages of project evaluation, and has been structured so that it provides information useful in both budgetary and economic planning of low volume roads.

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THE HIGHWAY COST MODEL
GENERAL FRAMEWORK

DRAFT REPORT

BY

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TABLE OF CONTENTS

			Page
Chapter 1		Introduction and Background to the Highway Cost Model	
	1.1	Scope of the Report	
	1.2	Role of the Model in Project Evaluation	
	1.3	Development of the Model	
	1.4	Analytic Framework of the Model	
	1.5	Applicability	
	1.6	Outline of the Report	
Chapter 2		Road Construction	
	2.1	Introduction	
	2.2	Date Requirements	
	2.3	Quality Estimates	
	2.4	Cost Estimates	
Chapter 3		Road Deterioration and Maintenance	
	3.1	Purpose of the Model	
	3.2	Inputs	
	3.3	Outputs	
	3.4	Major Categories of Maintenance	
	3.5	Paved Roads	
	3.6	Maintenance of Paved Roads	
	3.7	Unpaved Roads	
	3.8	Deterioration of Gravel Roads	
	3.9	Deterioration of Earth Roads	
	3.10	Maintenance of Unpaved Roads	
	3.11	Maintenance Requirements for both Paved and Unpaved Roads	
	3.12	Maintenance Policy Options	
Chapter 4		Vehicle Operating Costs and Traffic	
	4.1	Introduction	
	4.2	Data Requirements	
	4.3	Costs of Operation	
	4.4	Traffic Estimates	
Chapter 5		The Yala-Busia Case Study (Abridged)	
	5.1	Introduction	
	5.2	Input Data Documentation	
	5.3	Analysis of Output	

FIGURES

		Page
1.1	Structure of Highway Cost Model	
2.1	Division of Road into Segments	
2.2	Contour Line Description of Alignment	
2.3	Digital Terrain Description of Alignment	
2.4	Earthwork Quantities vs. Number of 10' Contour Lines Crossed	
2.5	Linear Approximation of Earthwork Quantities vs. Contour Lines Crossed	
2.6	Number of Culverts vs. Number of Low Points	
2.7	Distribution of Culvert Sizes	
2.8	Length of Culverts	
4.1	Computation of Axle Loads	
5.1	Cross-Section of Yala-Busia Road	

TABLES

		Page
2.1	Unit Costs	
2.2	Items of Work by Project Type	
2.3	Composition of Bituminous Surface Treatments	
3.1	Relationship between Structural Number, Cracking, and Equivalent Standard Axles	
3.2	Maintenance Activities and Quantities	
4.1	Vehicle Characteristics	
4.2	Vehicle Categories	
4.3	Components of Vehicle Operating Costs	
4.4	Coefficients for Speed Equations	
4.5	Coefficents for Fuel Consumption on Rough Paved Roads	
4.6	Claffey's Multipliers for Fuel Consumption on Rough Paved Roads	
4.7	Oil Consumption Rates	
4.8	Coefficients for Vehicle Maintenance Equations	
5.1	Existing Alignment and Environmental Data for Yala-Busia Road	
5.2	Final Highway Alignment	
5.3	Construction Unit Costs	
5.4	Maintenance Policies	
5.5	Maintenance Unit Costs	
5.6	Vehicle Descriptions	
5.7	Base Traffic	
5.8	Annual Growth Rates	

I. INTRODUCTION

1.1 Scope of the Report

This report describes an analytic model--the Highway Cost Model--for use in evaluating alternative design and maintenance strategies for low-volume roads. The focus of the model is on project-level engineering decisions and their implications for total transport costs. The types of decisions which are within the scope of the model include the choice of alignment, geometric standard, surface type, maintenance policy, and construction and maintenance methods. The costs considered include construction, maintenance, and road user costs, all of which are estimated in terms of the labor, equipment and material resources required. The model may be used at both the prefeasibility and feasibility stages of project evaluation, and has been structured so that it provides information useful in both budgetary and economic planning of low volume roads.

1.2 Background

In preparing or evaluating investment proposals for low-volume roads, planners may address a variety of issues. Foremost among these are to identify the objectives of the project and to determine the extent to which they are achieved in any specific design. Among the objectives which are often cited as justifying investment in roads are the provision of administrative and social services to isolated regions; access to areas with development potential; increased transport capacity; and reduced transport costs. A second area of concern may be to evaluate the role of a particular link in the development of the overall network; this type of analysis is of particular importance when a road will compete with other roads or other modes of transport--now or in the future. A third area of concern is to fit the project into an overall development program, both in terms of the financial and other resources that it will require, and in terms of its objectives.

The above issues constitute some of the broad range of topics which are generally considered in the planning and evaluation of road projects. In a well run planning organization, they will be considered in such a way that a variety of alternatives, together with their most relevant implications, are analyzed and presented to decision makers.

Within this framework of issues, however, there is an important subset of problems which has generally been ignored by planners but which is of particular interest to highway authorities--the selection of design and maintenance standards. While the choice of standards is sometimes obvious--as in the construction of an unimproved track to provide access to an isolated and undeveloped region--there appears to be a broad range of projects where planners provide little or no guidance, and for which the choice of engineering standards has important budgetary and economic implications.

For example, in deciding whether to improve an existing gravel road in order to reduce vehicle operating costs, planners may compare the costs of using and maintaining the existing road with the costs and benefits of constructing, maintaining and using the new paved road. If the economic return from paving the road is high enough, the project will be recommended.

At a more detailed level however, the Highway Authority may be interested in the following issues: should the road be surface-treated, or paved with asphalt concrete? What should be the thickness of the base, sub-base and surface coarses, and what types of materials should be used? How long will the road last before improvements are required, and what will be the nature of these improvements? Can the life of the road be extended through improved maintenance? Each of the possible alternatives implies a different stream of construction and maintenance expenditures,

and a different salvage value for the road at some specified point in the future. In addition, if the project is to be financed externally, the different alternatives may result in a different allocation of costs between the highway authority and the lending agency. Similarly, if the road is allowed to deteriorate, there will be a shift in costs from the highway authority (if deterioration is the result of low maintenance) or the lending agency (if deterioration is the result of an initial low design standard) to road users. The extent of this shift will depend on how well the pavement was designed originally and on the specified level of maintenance; the costs involved may vary over a wide range.

Tradeoffs similar to those described above may exist on other types of projects. For example, in new road construction it may be possible to vary geometric standards within a relatively broad range to achieve different tradeoffs between initial construction expense and future costs of using the road. Each time a lower standard is considered, the designer is effectively shifting costs from the highway authority to transporters and through increased tariffs, to the people of the region. At some point, there should be an overall minimum--but whether or not this is the standard which actually is seclected will depend on whether there are sufficient funds available for construction, and more generally on the manner in which government decision makers choose to allocate costs between different parties, in order to achieve social objectives.

Unfortunately, the practical difficulties of undertaking the above types of analysis on a comprehensive, project-by-project basis are enormous. Up until recently, relatively little has been known about the relationship between design maintenance standards, and their implications for maintenance and user costs. And while considerable attention has been focused on the problem of estimating construction costs, the resulting methods have been either simple and inaccurate, or

overly detailed. In short, there hasn't been any way of analyzing a large number of engineering alternatives, and of accurately assessing their implications.

In summary, there appears to be a broad range of projects for which engineering solutions will have different implications for the timing and magnitude of project costs and benefits, and for the allocation of these costs and benefits among different groups--including the highway authority, lending agencies, transporters, and the population of the region to be served by the road. Unfortunately, highway authorities have had relatively little guidance, and have lacked the analytic methods, for making rational choices between different engineering possibilities. It is to provide a sound basis for making these choices that the Highway Cost Model has been developed.

1.3 Analytic Framework

The basic function of the Highway Cost Model is to estimate construction, maintenance, and user costs for a road which has been designed and maintained to specific standards. This is done by simulating the life of the road from initial construction, through periodic upgrading, and through the yearly cycle of use, deterioration, and maintenance. The basic structure of the model--including data requirements, simulation framework, and the results produced--is shown in Figure 1-1.

The data requirements of the model are generally consistent with information available from national road transport studies, and with the data normally associated with the prefeasibility or feasibility stages of project evaluation. For data base management purposes, this information may be organized into i) national or regional standards, which encompass all road types and the full range of maintenance practice, and

which can be expected to be stable over a period of years; ii) highway program parameters which establish a uniform base for evaluating all projects within a program, and which should be reviewed on an annual basis; and iii) project parameters, which are specific to a particular project, and which will be updated as the project proceeds through the various pahses of the development process.

The simulation of the life of the road is accomplished by determining construction and maintenance activities to be performed, and by estimating road conditions, traffic volumes, and all associated costs on a year by year basis through the analysis period. The specific operations undertaken in each year are as follows:

A construction submodel schedules projects, estimates construction quantities and costs, allocates a percentage of construction costs to the current year, and updates the status of the link as projects are completed. The various types of projects which may be undertaken include new construction; pavement reconstruction or overlaying,widening, and the realignment. Estimates are prepared using different approaches depending upon the availability of data and the state of the design. Updating of the road includes the opening of sections to traffic; and the abandonment of older sections.

A traffic submodel makes a preliminary estimate of the current year's traffic based on the previous year's traffic and anticipated growth.

A road deterioration and maintenance submodel estimates the average road surface conditions for the year as a function of the initial design standard, the volume and composition of the traffic during the year, the local environment, and the specified maintenance policy. Surface deteioration may be estimated for both unpaved and paved roads.

A range of typical maintenance activities are specified for each surface type on either a scheduled or demand responsive basis, and are priced according to the amount of maintenance which is required. The condition of the road is expressed in terms of roughness, rut depth, cracking and patching (paved roads), and looseness and moisture content (unpaved roads).

The user cost submodel estimates the costs of operating vehicles over the road as a function of surface type and condition, and the design geometries (grade, horizontal curvature and road width). The components of vehicle operating costs include both running costs (fuel, oil, tires etc.), and time costs (depreciation insurance etc.). These estimates are prepared for a fleet of vehicles representative of those which will actually be using the road.

The results of the simulation include a record of expenditures incurred by the Highway Authority for capital improvements and maintenance; the costs incurred by road users; and a detailed history of the status and deterioration of the road. Construction and maintenance costs are broken down into labor, equipment, material, overhead and profit components by line item. Vehicle operating costs--including fuel, oil, tires, maintenance parts and labor, depreciation, and other time and utilization costs--are estimated for each type of vehicle using the road.

All estimates are made in terms of physical quantities, from which costs are obtained by applying the appropriate unit rates. The model can therefore be used within any monetary system, and is not affected by changes in relative prices.

All costs are estimated in both financial and economic terms.[1]

1.4 Development and Use of the Model

The selection of design and maintenance standards for low volume roads has been an area of particular interest to the World Bank, in conjunction with its work in financing road construction in less developed countries. Accordingly, since 1969, the Bank has sponsored or co-sponsored a series of research projects in this area under the aegis of the Highway Design Standards Study. The first phase of this study was completed at MIT in 1971 and resulted in a framework for relating design and maintenance standards to the total costs of transport--including costs incurred for the construction, maintenance and use of the road.[1] In addition to providing an integrated framework for evaluating design standards, the approach was the first one to explicitly consider the effects of road deterioration and maintenance in terms of their impact on planning decisions. However, a major conclusion of the study was that there was very little empirical data available on the pattern of deterioration for different types of roads, and on the relationship

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(1) Financial costs represent actual monetary expenditures for vehicle operations, and for road construction, and maintenance activities. Thus, they are required for budgeting purposes, and to enable reasonable assumptions to be made about user behavior where alternate routes or modes of transport are available. Economic costs represent the costs to the economy in terms of the resources consumed. In most cases taxes, duties, subsidies and other government transfer payments do not constitute a real social cost, so the economic costs of resources must be expressed net of all transfer payments.

(2) F. Moavenzadeh, J.H. Stafford, J.H. Suhrbier, J. Alexander, IBRD Staff Working Paper No. 96 Highway Design Standards Study Phase I: The Model January 1971.

between design standards, surface condition and road user costs.[1]

Subsequently, the Transportation and Road Research Laboratory, as part of the second phase of the World Bank study, conducted extensive field investigations in Kenya in the measurement of road user costs and the deterioration of low standard roads. These studies included i) the measurement of speed and fuel consumption for different types of vehicles on roads designed to different standards and with different surface conditions; ii) a survey of fleet owners to obtain estimates of tire consumption, and maintenance, and depreciation costs; and measurements of road deterioration for gravel and surface treated roads under different maintenance policies and traffic conditions. The results of these studies are available from TRRL as a series of reports.[2][3]

The Bank is now preparing to undertake additional studies to investigate a wider range of design standards and vehicle operating conditions in other parts of the developing world.

The current version of the Highway Cost Model, as developed for AID program, utilizes the framework developed in Phase I of the World Bank

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[1] The major source of data on the deterioration patterns of high standards paved roads was the AASHO Road Tests. At that time, there was very little comparable data available for the deterioration of earth, gravel, or low standard paved roads. Most of the data on user costs was derived from DeWeille; the deficiencies of these and other sources have been discussed in Highway Design Standards Study: Phase II Background Summary and Evaluation of TRRL/IBRD Kenya Study. International Bank for Reconstruction and Development, January 1975.

[2] Hide, H., et al. The Kenya road transport cost model: research on vehicle operating ocsts. Department of the Environment, TRRL Report LR 672. Crowthorne, 1975 (Transport and Road Research Laboratory).

[3] Hodges, J.W. et al. The Kenya road transport cost study: research on road deterioration. Department of the Environment, TRRL Report LR 673. Crowthorne, 1975 (Transport and Road Research Laboratory).

study and incorporates the results of the TRRL field investigations in Kenya, as well as other technical information reported in the highway engineering field since 1970. Inevitably there are gaps; where these exist, reasonable assumptions have been made. It is anticipated, however, that some of these gaps will be filled in the course of the Bank's ongoing Highway Design Standards Study.

The user cost relationships currently in the Highway Cost Model are based on the TRRL results in Kenya and are for free flowing conditions and reflect driver behavior and the types of vehicles typical of East Africa. They do not incorporate the effects of congestion or non-motorized traffic on vehicle operations, nor do they incorporate the traffic interaction effects of single lane roads. In addition the Kenya results are for gravel and paved roads only.

The paved road deterioration and maintenance relationships are based on the AASHO road tests and on the results of the TRRL studies in Kenya. As such, their direct applicability is limited to relatively high standard asphalt concrete roads (structural number greater than 3.0), and to a limited range of traffic conditions and maintenance standards for bituminous treated roads on cement stabilized base (structural numbers between 2.5 and 4.0). The gravel road relationships are based on the TRRL results.

While the Highway Cost Model can be used outside the range of conditions described, results which are obtained should be critically evaluated and used with caution.

1.5 Outline of the Report

The structure of the report is as follows: Chapter 2 describes the procedures used for scheduling and estimating road construction; Chapter 3 describes the road deterioration and maintenance submodel; and Chapter

4 describes the methods used to estimate road user costs and traffic. Each of these chapters presents its own data requirements, methods, and results. The last part of the report--Chapter 5--illustrates the use of the model on a simple case study--the Yala-Busia Road in Kenya. The issues raised in the case study are choice of surfacing (surface-treated vs. gravel) and maintenance policy (light or heavy).

Figure 1-1

DATA REQUIREMENTS

National or Regional Parameters

Design Standards
- Geometric standards
- Pavement sections
- Material characteristics

Maintenance Standards
- Routine Maintenance Criteria for Earth Gravel and Paved Roads
- Resurfacing Criteria

Highway Program Parameters

Construction Unit Costs
Maintenance Unit Costs
Basic Vehicle Ownership and Operating Costs

Project Parameters

Traffic
Physical Characteristics of the Alignment
Specific Design and Maintenance Standards to be Studied
Schedule for Implementation

SIMULATION OF ROAD LIFE CYCLE

For each year in analysis period

Estimate costs for road construction or upgrading based on design standards and construction unit costs

Update the status of the road based on project completions

Preliminary estimate of this years traffic

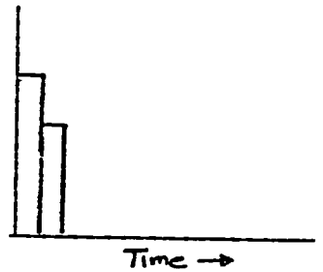
Estimate road deterioration, effects of maintenance, costs, and average surface conditions

Estimate user costs based on geometric standards, surface type and surface condition

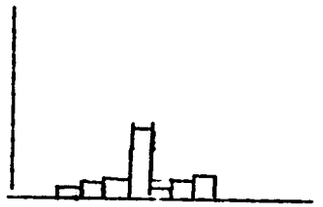
Update traffic projections based on actual user costs

RESULTS

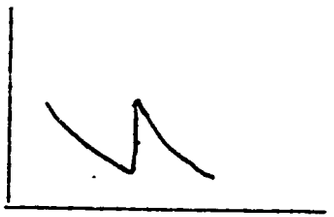
Capital Costs



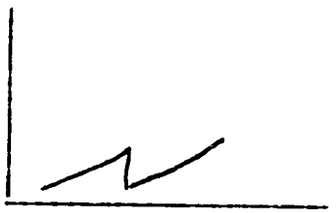
Maintenance Costs



Surface Condition.



User Costs s/v/km



II. ROAD CONSTRUCTION

2.1 Introduction

This chapter describes the road construction submodel, including the methods used to schedule construction and to estimate construction quantities and costs.

The key functions of the construction submodel are to relate construction costs to design standards, and to update the status of the road as projects are completed, so that the sections are available to traffic. Key features of the model are as follows:

Projects may be scheduled for any year in the analysis period, and may consist of new construction, pavement reconstruction, widening etc. Each project may affect one or more sections of the road--each having its own physical characteristics and design standards. Projects may be scheduled sequentially, as in staging. Construction costs are estimated in the year when the project is scheduled to start, but are allocated on a percentage basis over subsequent years, depending upon the duration of the project. When the project is completed, the road is opened to traffic.

Construction quantities are estimated as a function of the physical features of the alignment, the type of project, and the specified design standards. Costs then are estimated in both financial and economic terms by applying appropriate unit rates to these quantities.

The model employs somewhat different estimating procedures depending upon the state of the design. The data requirements of these procedures correspond roughly to the type of information available at the pre-feasibility and feasibility stages of project evaluation.

The organization of the chapter is as follows: Section 2.2 describes the data requirements of the model; Section 2.3 the quantity estimating procedures; and Section 2.4, the cost estimating procedures.

2.2 Data Requirements

The data requirements of the road construction submodel consist of the type of improvement and its scheduled starting and completion dates; the physical environment along the alignment; the proposed design standards; and unit costs, in both financial and economic terms.

2.2.1 Project Type and Schedule

The projects considered range from new construction to various forms of road improvement. The general characteristics of each type of project are as follows.

New Construction: This is the construction of a road where non currently exists or where the only existing road is an unimproved earth track. The principle items of work include clearing and grubbing, earthwork, drainage, major structures, and pavement. For estimating purposes, the assumption is made that existing improvements have no salvage value; that is, they will in no way reduce construction quantities or costs.

Pavement Reconstruction: This type of improvement includes the removal of the existing pavement structure, and the construction of new base and pavement layers. For estimating purposes, all road components other than the pavement structure are assumed to have full salvage value; pavement costs are incurred only for layers which are replaced or added.

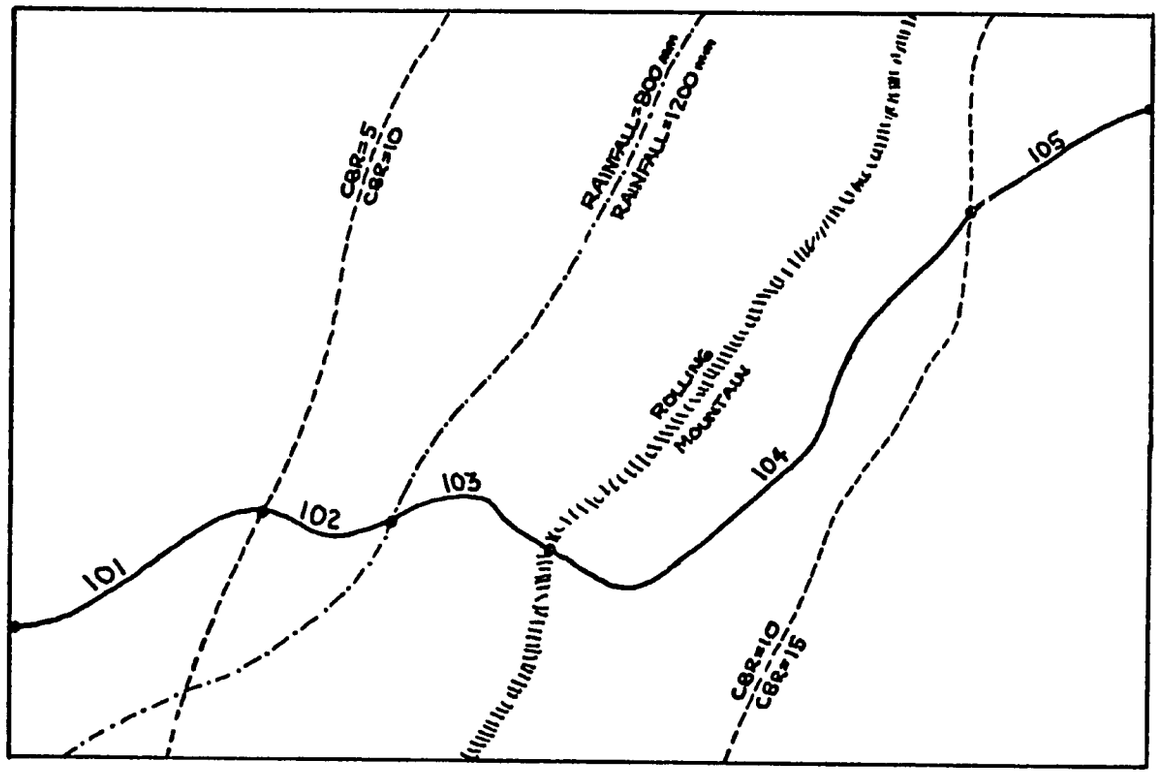
Widening: This type of improvement includes additional site clearing and earthwork; and extension of culverts and the riding surface. Quantities are estimated as the difference between the old and the new design standards. Demolition work is not explicitly included. Unit costs will be somewhat higher than for new construction. The work may also include minor changes in alignment or grade.

Realignment: Realignment consists of the construction of a new section of road to correct excessive curvature or grade in an existing alignment. Quantities and costs are estimated as for new construction.

Projects may have durations of up to four years and may be scheduled to start in any year of the analysis period. In terms of timing, the assumptions are made that the project starts at the beginning of the year in which it is scheduled, takes its full duration in years, and is completed at the end of the last year. Thus a project scheduled to start in 1970 and last for 2 years will be started at the beginning of 1970, and be completed at the end of 1971.

2.2.2 Physical Features of the Alignment

Topography, climate, geology, and soil jointly influence the choice of the most economical design, and the pattern of construction, maintenance and user costs incurred over the life of a road. Since individual characteristics can change--especially over a long alignment--the Highway Cost Model allows the project analyst to break the road into segments--each with its particular set of physical characteristics. The length of each segment will roughly correspond to the distance over which all characteristics are reasonably similar. When one or more characteristics change in such a way as to have implications for construction, maintenance or user costs, a new segment must be defined. An example illustrating the segmentation of the road for three factors--rainfall, soil strength, and area topography--is shown as Figure 2.1.



	101	102	103	104	105
CBR	5	10	-	-	15
RAIN	800	-	1200	-	-
TOPO	ROLLING	-	-	MOUNTAIN	-

FIGURE 2.1

The specific variables which are needed to describe the alignment are as follows.

Topography is an especially important factor in terms of its effects on road location and the other design elements (grade, sight distance, cross section, etc.). Generally speaking, the costs of constructing a road to a given standard increase with the roughness of the terrain; therefore it is quite common to reduce standards in such terrain--that is, to allow steeper grades, increased horizontal curvature and narrower section.

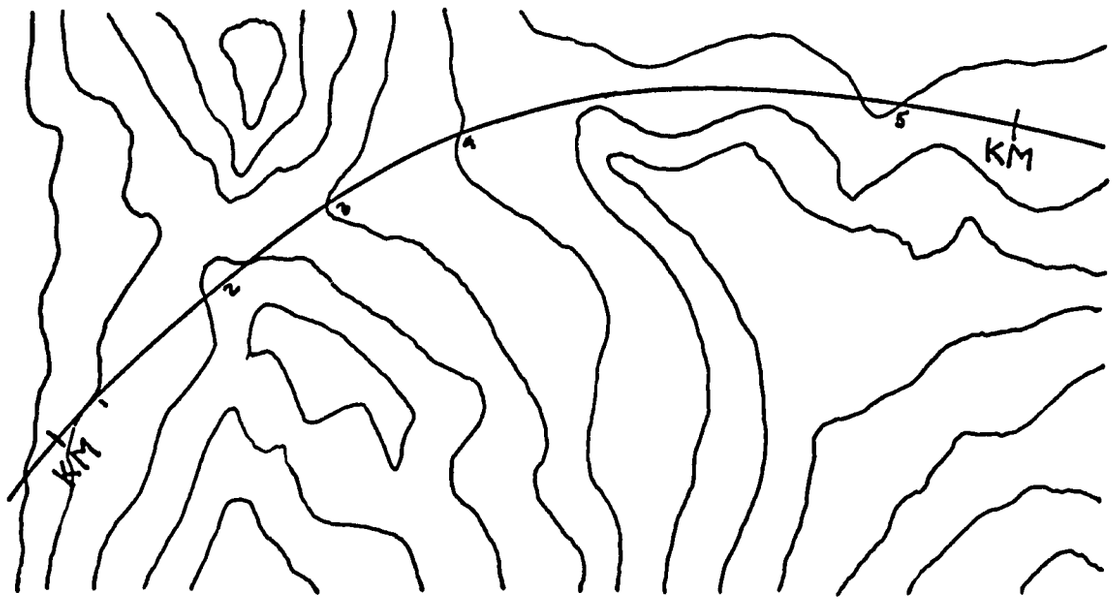
The Highway Cost Model classifies topography both for the area as whole and for the road alignment. This allows the analyst to account for situations where the two differ, as for example where the road is taking advantage of level terrain in a generally mountainous region.

The area classification scheme employs qualitative terrain descriptors as follows:

Flat - Average gradients from 0-2%
Rolling - Average gradients from 2-5%
Mountainous - Average gradients greater than 5%

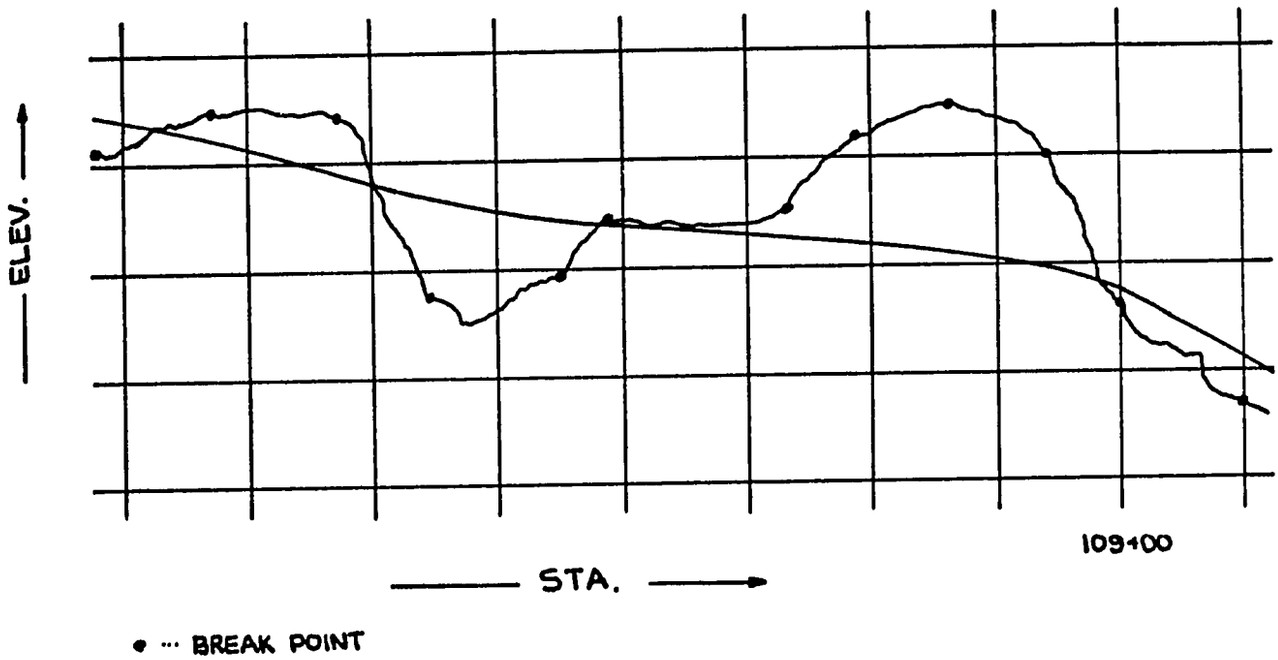
Area classification is required primarily in the estimation of drainage quantities and drainage maintenance requirements.

The choice of a topographic classification scheme for the alignment depends upon the type of study and the availability of data. For pre-feasibility estimates where mapping data is available, it consists of the number of contour lines crossed by the alignment in both the uphill and downhill directions (Fig. 2.2). At a more advanced stage of design, it consists of station, elevation and cross slope data for the ground profile. (Fig. 2.3)



$C = 5 \ \frac{\text{CONTOURS}}{\text{KM}}$

FIGURE 2.2


ELEV.
109+00
STA.
• ··· BREAK POINT

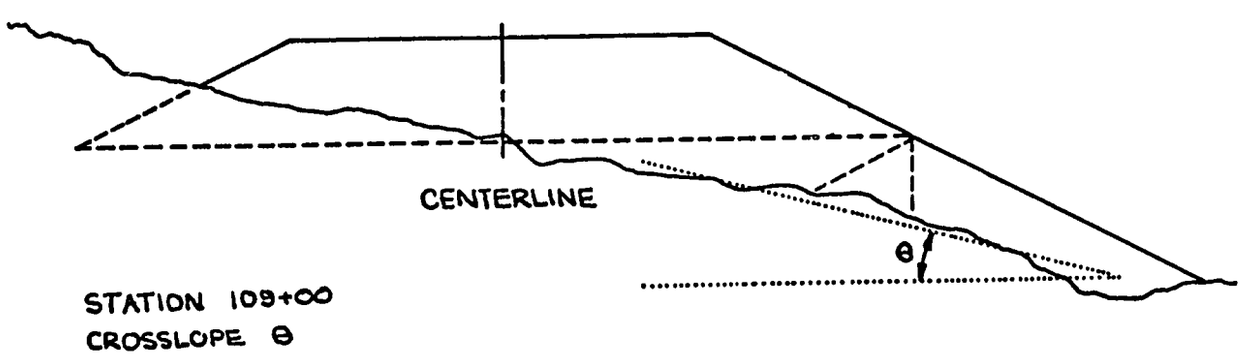

CENTERLINE
θ
STATION 109+00
CROSSLOPE θ

FIGURE 2.3

The primary use of alignment data is to estimate earthwork quantities. The alignment also influences user costs through its affect on the horizontal and vertical alignment of the road.

Climate: The climatological data which is required consists of the duration of the seasons, the total annual rainfall, and the maximum hourly rainfall. Since the Highway Cost Model is intended for use primarily in temperate zones, extreme temperature variations are not considered.

Seasonal information includes the length of the dry and rainy seasons, with a further differentiation between those periods in the rainy season when an unimproved earth road in the region would be wet, but passable; and the periods when it would be largely unpassable. If access to the road is controlled during and immediately after rainy weather, the impassable period corresponds to the number of days in the year when such controls must be exercised to exclude truck traffic for the greater part of the day.

Seasonal data is required in estimating the availability of the road to traffic and maintenance requirements.

The annual rainfall in centimeters is used in estimating road deterioration, and in computing annual drainage maintenance requirements.

The maximum hourly rainfall is used to estimate the distribution of culvert sizes for construction estimates.

Soil: Soil characteristics considered in the Highway Cost Model include their suitability as a construction material, strength, bulking and compaction factors, and type.

Suitability is used to classify earthwork quantities along the alignment. The basic classification is between material which is suitable for embankment and material which is unsuitable. If appropriate cost data is available for pricing purposes, unsuitable material may be further broken down into rock which must be blasted, rippable rock, unsuitable earth, etc.

The basis for classifying the material is as a percentage of the total quantity of material excavated. In principle, this percentage may change with the design standard--as for example, when a higher standard road cuts more deeply into ledge, thus altering the relative percentage of rock. In practice, however, there is usually little or no data on which to make such an assessment during the feasibility stages of the project. In the Highway Cost Model, percentage classifications are treated as constant across all design standards.

Strength is expressed as the California Bearing Ratio of the compacted subgrade. CBR has a major influence on the design of the pavement, and in its subsequent deterioration.

The bulking factor is the ratio of the volume of material after it has been excavated to its volume in the in-situ state. The compaction factor is the ratio of the volume of material after it has been compacted to the volume of material which is transported.

Soil type is a general descriptive parameter which can be used to relate the composition (gravel, sand, silt, clay, organic materials) drainage characteristics (well drained to poorly drained) and grading of soils used for earth roads to their trafficability during the dry and wet seasons.

Since there is very little data available on the performance of earth roads, this parameter has been incorporated into the model to allow the engineer to adjust the surface deterioration characteristics of earth roads on the basis of engineering judgement and local experience. Because of the limited nature of TRRL's results on earth roads in Kenya, the current version of the model differentiates only between soils with high and low clay contents.

Geology: The only geologic variables considered by the model are the average haul distances to quarries, borrow sites and other sources of local road building materials.

If material haul costs are to be priced separately, haul distances must be provided for each type of local road building material being considered for use in the road. These materials include sand, gravel and crushed rock for use in sub-base, base and surface courses of both paved and unpaved roads. Gravel types include coral, quartzitic, lateritic and volcanic gravels and are the ones for which TRRL has established specific gravel road deterioration relationships. The additional materials to be specified include those for which costs are different, or for which distinct material coefficients are defined, as required in the computation of pavement structural number.

2.2.3 Design Standards

The elements for which standards must be set in designing low volume roads include horizontal and vertical curvature, grade, width, and surfacing. The actual choice of standards is an interrelated function which depends on the physical environment, the volume and composition of traffic, the desired capacity of the road, safety, and the overall economics of the project. In practice, these decisions are often coordinated through the choice of a design speed, which ensures that the

various standards are consistent with one another--particularly from the standpoint of safety. Consistency implies that transitions between zones which have been designed to different standards (and therefore different design speeds) are gradual rather than abrupt, and that the curvature, gradient and width of the road within any zone are all appropriate for the design speed which has been selected.

There is some evidence, however, that the design speed concept as applied to low volume roads, may lead to uneconomic design solutions. In rapidly changing terrain, the most economic solution may be one where there are considerable variations in design standards over relatively short sections of road. So long as the driver can be safely made aware of these changes, then it is debatable whether the additional safety factor achieved using the design speed concept is worth the increased cost, particularly for very low volumes of traffic. Similarly the high rates of speed which can be achieved on level tangent roads in flat terrain should not necessarily cause the designer to increase road width beyond that which can be justified by the economics of the traffic volumes involved.

For the above reasons, the Highway Cost Model does not relate design standards to design speed. The designer is free to mix standards and to vary them continuously in searching for the most economic design solution. Safety is still an important factor, but one which must be considered outside the framework of the model.

The economic implications inherent in the choice of design standards are roughly as follows: improved geometric standards (width, curvature, grade) increase construction costs and reduce vehicle operating costs; improving the riding surface increases construction costs and reduces both maintenance and vehicle operating costs; improving drainage increases

construction costs, reduces maintenances costs, and on the lowest standard roads, leads to some reduction in vehicle operating costs. Specific design standards are discussed in the following paragraphs.

Horizontal Curvature is usually specified as the maximum degree of curvature or the minimum radius. However, since the Highway Cost Model has no mechanism for generating its own horizontal alginment, this standard must be inherent in the alignment which is being analyzed. The actual curvature of the alignment is expressed in total degrees per kilometer.

Cross-section: The cross-section consists of the riding surface width and slope; shoulder width and slope; ditch width and slope; the total width of the right-of-way; and slopes in cut and fill sections. Of these, the most critical dimension from the traffic point of view is the roadway width, which is usually treated as a function of traffic volumes and speeds, and vehicle dimensions.

The usual practice among designers is to reduce the cross-section in rougher terrain, in order to minimize earthwork quantities. This is frequently accomplished by reducing ditch dimensions, and less frequently, by reducing the dimensions of the shoulder.

Vertical Alignment: Vertical alignment standards must be set for maximum grade, and the length and radius of vertical curves.

The choice of grade influences construction costs through its impact on earthwork quantities; and user costs, primarily through reduction in speed and an increase in fuel consumption. The 1965 AASHO standards call for maximum grades on the order of 9% for their lowest standard road, but for certain conditions in the developing countries, maximum grades of up to 20% may be acceptable where grades are short and where the riding surface provides adequate traction.

Specifications for vertical curves are basically a function of sight distance and vehicular speeds. They are required for feasibility level estimates of earth work quantities, but do not otherwise enter into the model (sight and stopping distances are asssumed to be adequate in estimating actual vehicle operating speeds).

Surfacing: Surfacing must be specified in terms of material type, characteristics, and thickness, for all pavement layers in both the riding surface and shoulder. The basic types of surfaces which are normally considered for use in developing countries include earth, gravel and asphaltic concrete or bituminous treated paved roads. The choice of surface type is usually based on economic considerations. The details of the design, that is material types, specifications, and thicknesses are based on a combination of engineering and cost criteria.

The Highway Cost Model does not incorporate pavement design procedures. The reason for this is that pavement design practice varies considerably from place to place, and the prevailing methodology is usually one that has proven successful and is well-correlated with the local soil, climate and material availabilities. A second reason is that a built-in design methodology implies certain assumptions about future traffic, maintenance patterns etc., which are variables which are within the decision domain of the model. It is therefore left the to the analyst to specify different designs, and to study their economic implications through the use of the model.

Unimproved earth roads will generally have no paving costs; the costs of shaping the riding surface are treated as part of the earthwork grading operations. Improved earth roads may have sections where imported materials have been mixed with the in-situ soil; this should be included in the paving costs.

2.2.4 Unit Costs

Three approaches are generally taken in estimating construction costs, depending upon the phase of the project and the purpose of the estimate

- generalized unit costs applied to major end items of work e.g. cost of earthwork per kilometer of primary road in rolling terrain. This approach is often taken in developing pre-feasibility estimates of costs.
- adjusted unit costs derived from previous contracts, applied to specific work items e.g. cost per cubic meter of crushed stone base. This approach may be taken in preparing pre-feasibility level estimates, if sufficient data is available, and is the one usually taken in preparing feasibility estimates.
- detailed unit costs based on a careful evaluation of the contractor's probable methods, and the estimated labor, equipment and material requirements; applied to specific work items. This is the detailed approach to estimating which should be employed at the pre-bid stage.

In the current version of the model, the adjusted unit cost approach is used for both prefeasibility and feasibility level estimates. The major changes from the usual practice are to: 1) breakout the skilled and unskilled labor, equipment, material, and overhead and profit components of each unit cost--this breakdown may be based on approximate percentages applied to the contract unit cost, and is needed for the computation of the economic and foreign exchange components of total cost; and 2) to differentiate between the base transport cost for earthwork and construction materials, which is included in the basic unit cost; and the incremental transport cost--expressed as a cost per unit of material hauled per kilometer--which is used to account for hauls in excess of the free haul distance. The total unit cost data requirements are shown as TABLE 2-1. Separate unit cost data sets may also be provided for different types of projects, and for different regions

Item	Base Unit Cost - $/unit								Transport Cost - $/unit - km			
	Unit	Skilled Labor	Unskilled Labor	Equipment	Materials	Overhead Profit	Total	Free Haul	Labor	Equipment	Overhead Profit	Total
Clearing and Grubbing												
Light	Ha.	800.00	100.00	500.00	200.00	400.00	2,000.00					
Medium	Ha.	1,000.00	125.00	625.00	250.00	500.00	2,500.00					
Heavy	Ha.	1,200.00	150.00	750.00	300.00	600.00	3,000.00					
Earthwork												
Rock Excavation	M^3	3.50	2.50	4.00	2.00	3.00	15.00					
Common Excavation	M^3	1.25	.25	2.50		1.00	5.00					
Borrow	M^3											
Formation of Embankment	M^3	1.50	.20	2.70		1.10	5.50	3	.10	.10	.5	.25
Paving												
Subbase Pit Run Material	M^3	8.00	5.00	8.00	3.00	6.00	30.00	10	.40	.40	.2	1.00
Crushed Aggregate Base Coarse	M^3	10.00	6.00	12.00	4.00	8.00	40.00	10	.40	.40	.2	1.00
Surface Treatment												
Crushed Aggregate	M.T.	12.00	5.00	14.00	5.00	9.00	45.00	10	.40	.40	.2	1.00
Bituminous Asphalt	l.	.10		.10	.24	.11	.55					
Minor Drainage												
24" RCP	M.	50.00	30.00	10.00	30.00	30.00	150.00					
30" RCP	M.	65.00	40.00	15.00	40.00	40.00	200.00					
36" RCP	M.	80.00	50.00	20.00	50.00	50.00	250.00					
42" RCP	M.	95.00	60.00	25.00	60.00	60.00	300.00					
48" RCP	M.	110.00	70.00	30.00	70.00	70.00	350.00					

Table 2.1

Unit Costs for Construction of Bituminous Surface Treated Roads

of the country.

2.3. Quantity Estimates

The principle items for which quantities may be estimated include clearing and grubbing, earthwork, minor drainage structures, and pavement. Major structures are priced on a lump sum basis, and receive only limited discussion in this section. The relationships between the principle items of work and the major types of projects are shown in TABLE 2-2

TABLE 2-2

ITEMS OF WORK BY PROJECT TYPE

	Clearing & Grubbing	Earthwork	Pavement	Minor Drainage Structures
New Construction	x	x	x	x
Pavement Reconstruction(1)			x	
Widening(2)	x	x	x	x
Realignment(3)	x	x	x	x

(1) Pavement Reconstruction may consist of a major overlay on top of the existing pavement, or the removal of one or more layers of the existing pavement, and with the addition of new layers.

(2) Widening is estimated as the difference between the quantities for the old and new design standards.

(3) Realignment is estimated in the same way as new construction.

The quantity estimating methods described in the following sections may be used at both the prefeasibility and feasibility stages of project evaluation. The specific methods used to estimate clearing and grubbing, and pavement quantities are the same in either case, except that the variables are assumed to be known with a greater degree of precision. The earthwork estimating techniques differ radically. For prefeasibility estimates, the data requirements consist of a contour map showing the proposed alignment. For feasibility estimates, it is assumed that engineering has progressed to the stage that a vertical profile of the road is available. The methods for estimating drainage structures show some variation as follows: for prefeasibility estimates, it is assumed that culvert locations may be determined from maps, but that that have not been designed either as to type, diameter or length. For feasibility estimates, culvert locations, type and sizes are assumed to be known. Specific details of the Highway Cost Model quantity estimating procedures are as follows:

Clearing and Grubbing: Clearing and grubbing includes the removal of vegetation, trees and underbrush from along the road alignment in preparation for earthwork operations. Quantities are estimated in hectares based on the difficulty of conditions and the width and length of the right-of-way.

Conditions are specified as being either easy, normal or difficult depending upon the roughness of the terrain and the density of vegetation. The definition of what constitutes easy, normal and difficult is arbitrary from the standpoint of the model, but should correspond to the range of conditions which can be found in the country. One possible breakdown is as follows:

Condition	Description
Light	Culvitated areas; desert or semidesert; open planes
Medium	Heavy brush; lightly forested regions.
Heavy	Perciptous, broken terrain; heavily forested areas; jungle

The area to be cleared is estimated as

$$A_i = P_i/100 \times W \times (L \times 1000)/10{,}000$$

where A_i = area in hectares of clearing condition i
P_i = estimated percentage of clearing with condition i
W = width of right of way, in meters
L = length of road, in kilometers

Earthwork: Earthwork includes the excavation, hauling and placing of material; the formation and compaction of embankments, and the shaping of slopes. Quantities are measured in terms of cubic meters of excavated material as a function of cross section, ground and road profiles, and characteristics of the material to be excavated.

Since the availability of data on the ground and road profile can vary significantly at various stages of the project, the Highway Cost Model provides two separate procedures for estimating earthwork quantities. The first of these procedures relies on a statistical correlation between earthwork quantities, the design standard, and the rise and fall of the ground, and is based on the work of Augusto Soux of TRW Systems.[1]

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[1] Lago, Armando M., "Cost Functions and Optimum Technology for Intercity Highway Transportation Systems in Developing Countries," Traffic Quarterly, October 1968, pp. 521-553.

The second procedure uses the average end area method to compute earthwork quantities as a function of the cross-section, and the actual ground and road profiles. This procedure was developed by the Transportation and Road Research Laboratory for their Road Transport Investment Model.[1]

The TRW procedure assumes a fixed relationship between cut and fill quantities. and estimates excavated quantities without classifying the material. The unclassified material may be broken out into spoil, rock, etc. using rough percentage factors estimated on the basis of field surveys. Borrow is estimated as the difference between the assumed fill requirement, and the quantity of material suitable for embankment. Haul distances are not considered.

The TRRL approach estimates cut and fill quantities separately, and explicitly considers haul distance. The breakdown of excavated material into its various components is similar to the TRW model; that is percentages of spoil, rock, etc. are applied to the total quantity of excavated material. Borrow requirements are estimated as a function of total fill requirements, the % of cut material which is suitable for embankment, and the marginal haul distance at which it becomes cheaper to spoil the cut and borrow the fill. Haul distances are computed from a mass-haul diagram, which is automatically generated by the model.

Contour Line Model: The method used for estimating earthwork quantities at the prefeasability stage of the project is based on the work of Augusto L. Soux of the Systems Group of TRW Inc. This method estimates the volume of earthwork required to bring the roadway to grade as a function of the maximum allowable grade, road width, earth slopes in cut

[1] Robinson, R., et al. A road transport investment model for developing countries. Department of the Environment, TRRL Report LR 674. Crowthorne, 1975 (Transport and Road Research Laboratory).

and fill sections, and the number of contour lines crossed per unit length of road (Fig. 2-1).

Soux developed curves relating unclassified excavation quantities to the number of contour lines crossed for a variety of road standards and terrain types. For each standard, road profiles were fitted to 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. Earthwork volumes were computed using the average end area method and a single point digital terrain model and were then plotted against contour density. Curves typical of those which were fitted to these points are shown in Figure 2-4.

The approach used to estimate earth work quantities in Soux's computation was a simple trapezoidal prism formula:

$$Q = d(bh + zh^2)$$

where
- Q = the total earthwork volume between sections
- b = road width
- z = road side slope
- h = the difference between the elevation of the terrain and road profile
- d = road length

To expand the model to permit any combination of road width and road side slope, the earthwork volume versus contour density curves were split into two components, Q_b and Q_z, which are equivalent to the road width factor (h) and the side slope factor (h^2) in the above formula. This reduces the quadratic forumla to

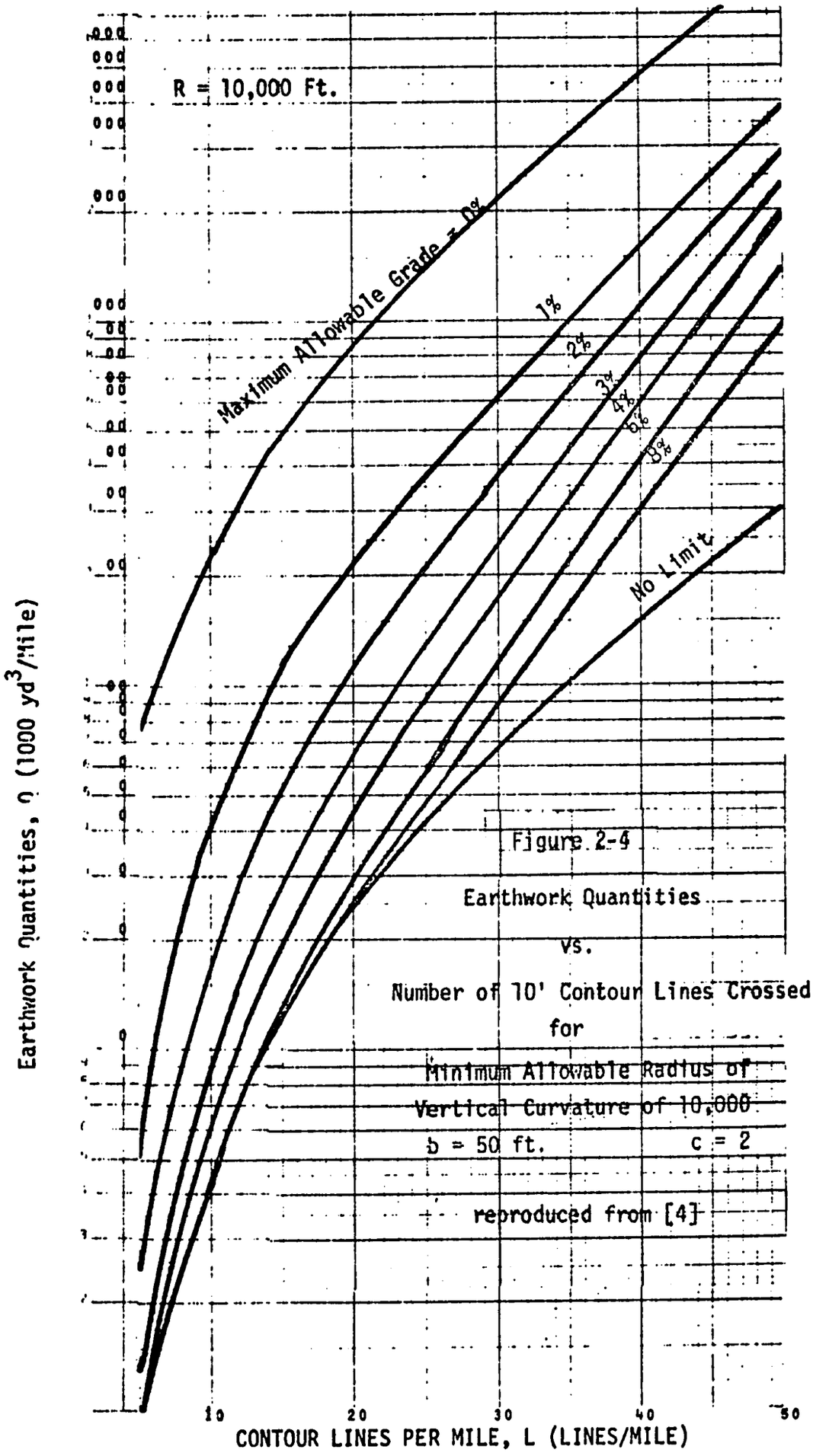


Figure 2-4

Earthwork Quantities

vs.

Number of 10' Contour Lines Crossed

for

Minimum Allowable Radius of

Vertical Curvature of 10,000

b = 50 ft. c = 2

reproduced from [4]

$$Q = d(bQ_b + zQ_z)$$

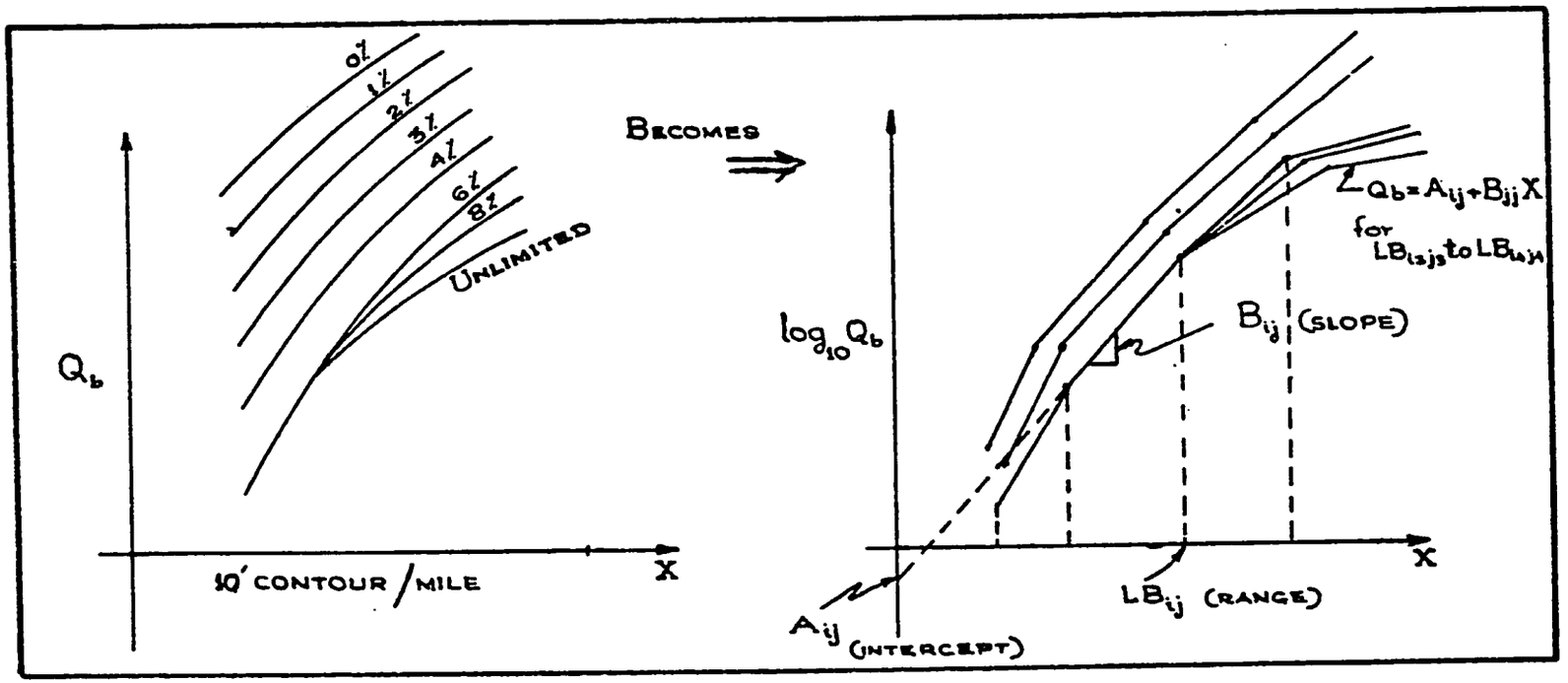
where Q, d, b and z are as defined above, and Q_b and Q_z are graphical functions of the maximum allowable grade and the contour density.

The estimating routine currently incorporated in the Highway Cost Model uses one set of these Q_b and Q_z curves. Since these curves are non-linear, they have been approximated by a series of linear segments as shown in Figure 2.5. The slopes, intercepts and range (of contour density) of these segments have been stored in matrix form where rows represent the maximum allowable grade and the columns represent the range of contour density.

The use of the rate of rise and fall of the terrain and maximum grade of the profile as a basis for developing quick estimates of earthwork quantities represents a new approach, and while the resulting model is properly sensitive to variations in topography and design the current version of the model and the data on which it is based should be used with great care. In particular, the following problems may impede the usefulness of the current model:

1. The methodology was developed using a limited data base and was oriented toward high standard roads.
2. The data were obtained using a one point terrain model and level cross-section, ignoring the effects of ground cross-slope, and will tend to underestimate volumes.
3. The orignial 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.

Figure 2.5 Linear Approximations of Earthwork Quantities vs. Contour Lines Crossed.



The TRW results appear to be useful, but should be recalibrated for each country in which the model is implemented to reflect local design practice and available mapping standards. This can be accomplished by studying a range of completed projects for which earthwork quantities are available, and by limiting the scope of the study to locally relevant standards.

Digital Terrain Model: For feasibility level estimates of earthwork quantities, the Highway Cost Model uses procedures developed by the Transportation and Road Research Laboratory for their Road Transport Investment Model. These procedures compute earthwork quantities using the average end area method, where the area at any section is a function of the height of fill or depth of cut, the dimensions of the road cross-section, and the cross slope of the ground. The volume of earthwork is computed as a function of the distance between sections and the section areas.

The data requirements of the model consist of the ground profile, the road profile, the cross-section, the thickness of the pavement structure, the characteristics excavated material, and the marginal haul distance. The ground profile is defined by the station, elevation and cross fall at break points along the alignment. The road profile consists of the station, elevation, and curve length and radius at each vertical point of intersection. The characteristics of excavated material consists of bulking and compaction factors, and the percentage classification of material into spoil, rock etc. The marginal haul distance is the distance at which it becomes cheaper to spoil cut material and borrow fill.

The calculations of earthwork quantities are based on standard engineering computations and are described more fully in the users manual. Haulage is estimated by plotting a mass haul diagram, and estimating the location of the balance line.

2.3.3 Small Drainage Structures

The drainage and water crossing requirements of low-standard roads may be accomodated through several means, including the construction of ditches, culverts and bridges. For purposes of analysis, the costs involved are broken up as follows: the costs of constructing ditches are included under earthwork (discussed previously); the costs for furnishing and installing box, slab and pipe culverts are included under minor drainage structures; and the costs of bridges and major culverts are included under major structures.

The primary functions of culverts are to transport surface runoff originating on or near the right of way; and to handle flow in small streams which cross the right of way. The activities involved in installing culverts include trench excavation and backfill: the placing of base materials; and the construction of the culvert and required head and end walls. Pipe culverts may either be purchased by the contractor or constructed in his yards and will then be transported to the job site and laid in place. Box and slab culverts are usually constructed in place.

There has been relatively little research on the estimation of culvert quantities for prefeasibility level cost estimates. Lago[1] reviewed a cross-section of projects in an attempt to correlate drainage requirements with road width and terrain type, but the results show wide variations from actual quantities when applied to specific projects. For logistics planning purposes, the US Army assumes 3.7 culverts/

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[1] Armando M. Lago, "Cost Functions and Optimum Technology for Intercity Highway Transportation Systems in Developing Countries," Traffic Quarterly October 1968 pp. 521-553.

kms in flat terrain to 13 culverts/km in mountainous terrain,[1] but again, these are system wide averages which may bear little relationship to the actual quantities required on a specific project. Some guidelines appropriate for planning level estimates are discussed by Vance,[2] but no supporting data is provided.

For prefeasibility estimates, the method used in the Highway Cost Model to estimate drainage requirements is based on an approach suggested by McCoomb,[3] who analyzed data regarding the number, size and length of culverts based on a limited cross-section of Canadian projects.

McCoomb plotted the number of low points along an alignment (taken from a contour map) against the number culverts actually installed, and observed roughly on a one to one correspondence between the two variables (Figure 2-6). Therefore in the approach suggested here, the number of culverts is estimated from aerial photographs or contour maps by counting the number of such points, and by making appropriate adjustments based on locations where culverts are known to be required, either because of an existing stream bed, or because of the need to drain surface runoff from one side of the road to the other.

McCoomb also observed a consistent distribution among culvert sizes, the number of each type decreasing monotonically with increasing culvert size (Figure 2-7). Such a distribution can therefore be used to differentiate between the different sizes of culverts, given their total number.

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(1) United States Army Staff Officers Field Manual: Organizational, Technical and Logistical Data: Unclassified Data, 1969 (FM 101-10-1).

(2) Vance, Lawrence Lee, Jr. Cost Functions for Comparison of Low-Cost Transportation Technologies, University of California, Berkeley, D. Eng. Thesis, Civil Engineering, 1970.

(3) McCoomb, Lloyd A. "Predictive Cost Models for Highway Construction" Unpublished SM Thesis, MIT Cambridge, MA 1970.

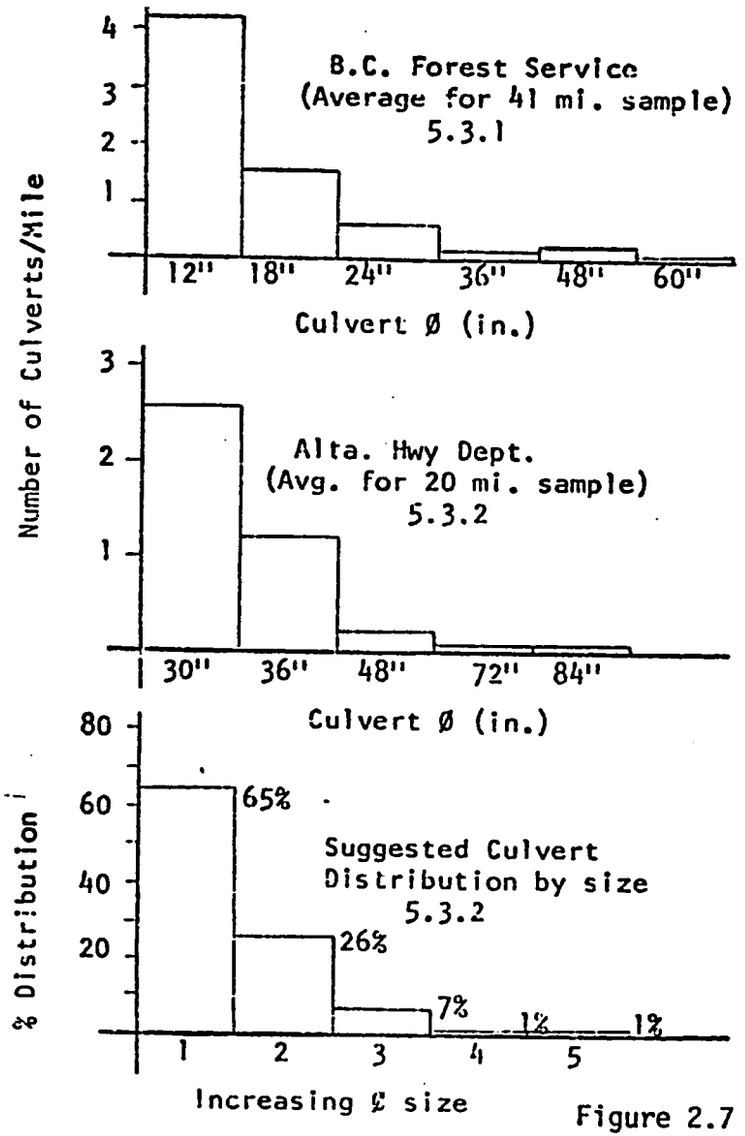

Figure 2.7

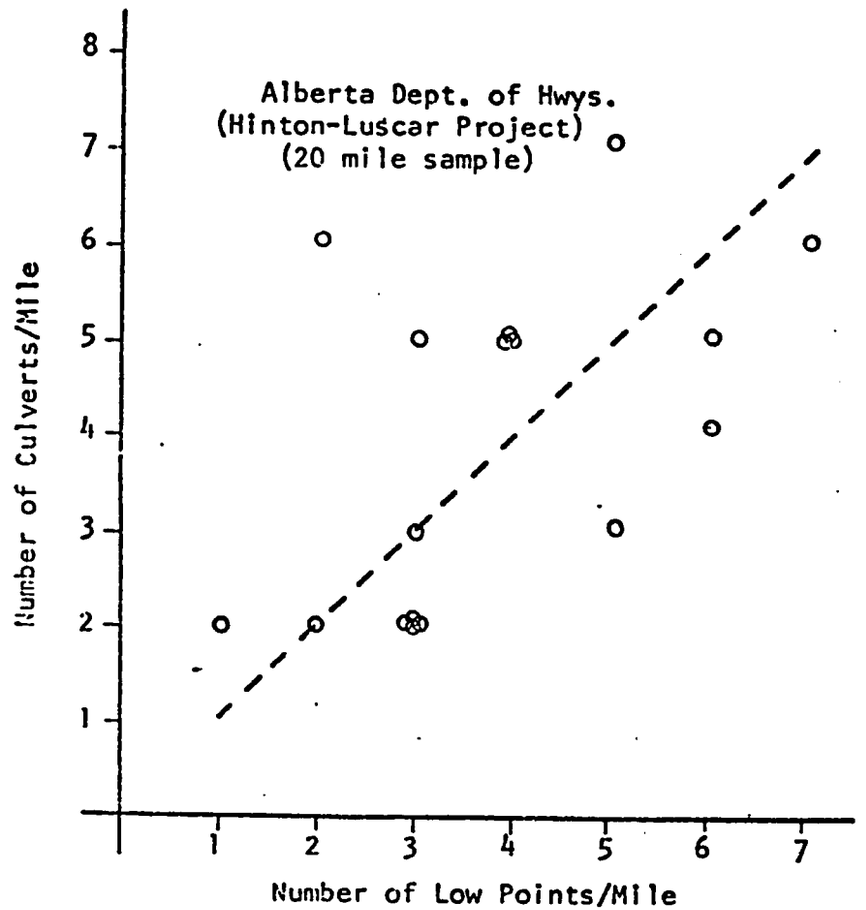

Figure 2.6

The culvert sizes included in the distribution will depend upon a number of factors, including the preferences of the local highway authority, the design criteria[1] used for a particular standard of road, and the hydrology of the area. In practice, it may therefore be necessary to have a number of different distributions built into the model for different design standards and different hydrological conditions. Although the current version of the model has only one distribution, provision for the addition of others has been allowed for by creating a matrix of distributions which may be indexed by design standard, area topography (flat, rolling and mountainous) and maximum hourly rainfall (low, medium and high).

For feasibility estimates, the number of culverts of each size to be used on the project must be provided by the analyst.

The actual length of each culvert depends on road width, cross slope, the height of fill, and the skew angle of the culvert. In his analysis of Canadian data, McCoomb found that the key explanatory variables were culvert size and road width (Fig. 2.8). The effect of culvert size arises from the fact that the larger sizes are generally associated with deeper fills. The increased scatter of the points for the larger sizes is due to the limited number of observations in this range. In the current version of the Highway Cost Model, these factors have both been accounted for by assigning a width parameter to each culvert size. This factor is then multiplied by the total formation to determine the length of the

[1] The effect of drainage design criteria are as follows. Culverts are usually designed to handle the runoff from a storm which can be expected to recur with a given frequency. For example, if a culvert is designed for a 25 year storm, this implies that the probability is 1 in 25 that the culvert will reach or be extended beyond its capacity in any given year. The longer the selected recurrence interval, the larger the storm for which the culvert must be designed, and the larger is the size of the culvert. Generally speaking, drainage facilities on roads which are designed for very low volumes of traffic, and on which some storm drainage can be tolerated, will be designed using shorter recurrence intervals than on more heavily traveled roads and will therefore have smaller average culvert sizes.

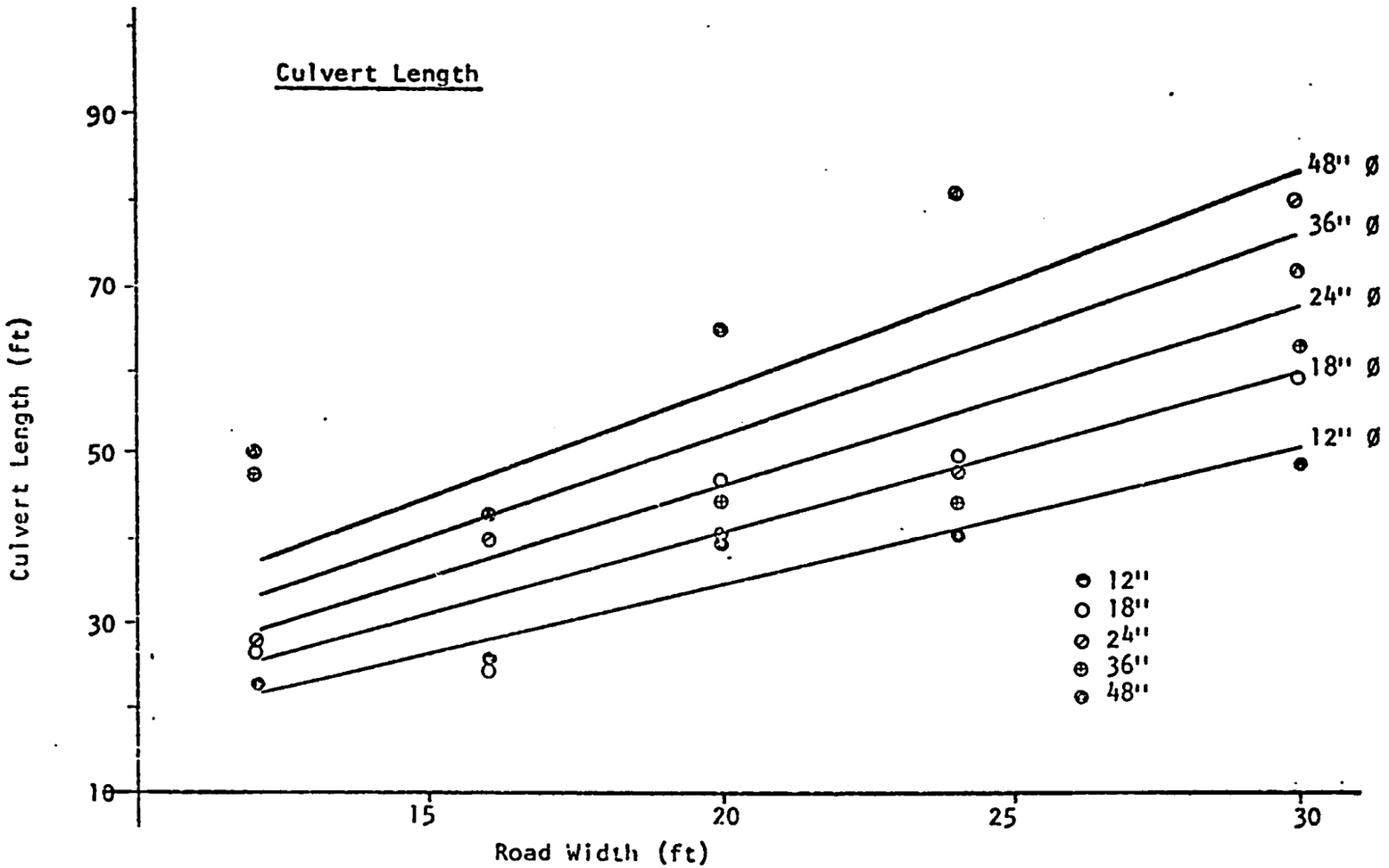
Culvert Length
Culvert Length (ft)
90
70
50
30
10
15
20
25
30
Road Width (ft)
48" Ø
36" Ø
24" Ø
18" Ø
12" Ø
12"
18"
24"
36"
48"

Figure 2.8

culvert. This procedure is used for both prefeasibility and feasibility level estimates.

To summarize, the total number of culverts, N_T, is determined from a contour map or preliminary engineering drawings. The number of culverts of each size is estimated from

$$N_i = F_i * N_T$$

where N_i = number of culverts of size

F_i = percentage of the total number culverts which are of size i; treated as a function of designstandard, area topography, and the maximum hourly rainfall for prefeasibility estimates; and provided by the user for feasibility estimates

and the average length of each size culvert is estimated from

$$L_i = F_i * RW$$

where L_i = length of culverts of size i

F_i = width factor for culverts of size i

RW = road width from outside edge of shoulder to outside edge of shoulder.

Pavement: Paving operations included the furnishing, hauling and placing of sub-base, base and surface materials for improved earth, gravel and paved roads.

Since the materials used in the construction of shoulders may be of a different type and thickness than those used in construction of the traveled way, separate specifications may be provided for the shoulder and roadway portions of the pavement cross-section.

The estimation of pavement quantities is a straightforward series of calculations based on the volumes of areas of individual layers:

$$V_i = (T_i/100) \times W \times (L \times 1000)$$

$$A_i = W \times (L \times 1000)$$

where V_i = volume of material type i in cubic meters
A_i = area of material type i in square meters
T_i = thickness of material i in centimeters
W = width of riding surface or shoulders, as appropriate, in meters.
L = length of the road in kilometers

The volume and area relationships are both required to account for different approaches to material pricing. Crushed stone, for example, may be priced on a cubic meter basis, while bituminous treatment is often priced on a square meter basis.

If material haul costs are to be priced separately, further disaggregation is possible for mixed materials (bituminous treatments, asphalt concrete, etc.) using a material composition table as shown in TABLE 2-3. These tables may be setup using designs typical of a country where the model is to be implemented.

TABLE 2-3

QUANTITIES OF MATERIALS FOR DOUBLE BITUMINOUS SURFACE TREATMENTS

Type of Surfacing	Aggregate -kg/m^2	Bitumen - l/m^2
DBST	27	2.6

2.4 Cost Estimates

Construction costs are estimated for three categories of work: i) direct work items such as site clearing, earthwork, paving and minor drainage for which quantities are estimated, and which are priced on a unit cost bases; ii) direct work items such as bridges and other major structures which are priced on a lump sum basis; and iii) indirect items such as mobilization, camp consturction, and administration of the project, which are priced on either a lump sum basis, or as a percentage of the total costs for direct work items. The costs of the first two categories of work are termed direct costs; the costs for the last category are indirect costs.

2.4.1 Direct Costs

Direct work items for which quantities are estimated are priced using unit costs such as those shown in TABLE 2.1. Assuming that bid prices are not unbalanced, and that it is possible to determine the percentage of overhead and profit allocated to each work item, the basis for these unit costs may be prevailing unit prices on current contacts although it may be necessary to make additional adjustments to reflect different work conditions, future cost escalation etc.

The methods used to estimate these costs is as follows: the base unit costs for each work item are multiplied by the quantity of that work item to arrive at the labor, equipment, material, and profit and overhead components of total cost. For items which have component materials (such as surface treatment in TABLE 2.1) unit costs are applied for both the finished product (the surface treatment) and the component materials (crushed aggregate and bituminous asphalt), of costs are provided. This allows the estimator to price such items on either finished item basis, a component material basis, or a combination of the two (differentiating between material production and placement costs).

Transportation costs are computed for appropriate earthwork paving and drainage items when the haul distance for material within a segment exceeds the free haul distance reflected in the base unit cost. Transportation costs are added to the base costs to arrive at the total cost of the item.

All direct cost items for which quantities are not esitmated are priced on a lump sum basis.

2.4.2 Indirect Costs

Indirect costs are accounted for on either a lump sum basis or as a percentage of total direct costs.

A distinction is made between indirect costs included under this section and the overheads incorporated in direct unit costs in order to reflect different contracting practices. In some cases all or most indirect costs will be allocated to direct cost items; while in others certain indirect costs may be treated as separate bid items. Camp construction is a common example. This latter category of costs is handled as described in this section.

III. ROAD DETERIORATION AND MAINTENANCE

3.1 Purpose of the Model

The deterioration-maintenance model computes two types of information essential to the successful operation of the total cost model: maintenance costs and road surface condition. These are computed for each year of the analysis period. The maintenance cost is added directly to the total highway cost, while the road surface condition is used by the user cost model to estimate road user costs, which in turn are used to predict the volume of traffic attracted to the raod, which in turn causes deterioration in the road surface condition. Thus, the surface condition predicted by the maintenance-deterioration model affects the total highway cost indirectly, but very importantly, through its effect on road user costs.

3.2 Inputs

The five basic types of variables which affect the maintenance cost and road surface condition are:

1. Environment and aging
2. Traffic volume and composition
3. Characteristics of the highway
4. Maintenance standards
5. Maintenance unit costs

The specific variables needed to estimate surface deterioration, the effects of maintenance, and the resulting surface condition are discussed individually in the sections dealing which each type of surface (unpaved, paved). The estimation of costs is treated separately in the last section of the chapter.

3.3 Outputs

The output from the maintenance model consists of maintenance expenditures for the year, and an estimate of average road surface conditions. Maintenance expenditures are estimated by first determining the units of work required for each maintenance activity, and by then applying appropriate unit rates. The results may be expressed on an activity by activity basis for each road segment, or as a total for the entire year.

Roadway surface condition is described in terms of surface roughness, rut depth, area of cracking and patching (paved roads only), serviceability (paved roads only), and surface thickness (gravel roads only). Surface condition is described also in terms of surface moisture and depth of loose material (unpaved roads only). These surface condition parameters are computed for a maximum of three subdivisions or seasons of the year, the length of which are specified by the user. The three subdivisions are: dry season (when earth and gravel roads are dusty), wet season (when earth and gravel roads are not dusty), and impassable season (when earth roads become impassable and gravel and paved surfaces are wet a high percentage of the time). These parameters are used by the user cost model, along with curvature, grade, etc., to compute road user costs for each year.

3.4 Major Categories of Maintenance

Maintenance-deterioration estimates are made for the following categories of maintenance activities: the riding surface of paved and unpaved roads; shoulder maintenance on paved and unpaved shoulders; drainage maintenance and vegetation control. Primary emphasis in the following discussions is placed on the problem of surface deterioration and maintenance, since this usually accounts for over half the cost of maintaining low volume roads, and because of the interrelationship between surface conditions and construction,maintenance and user costs.

3.5 Paved Roads

The deterioration of paved roads is handled in two ways, depending on whether the base is stabilized or unstabilized. For flexible pavements with granular bases, the general AASHO Road Test[1] results are used, with some modifications. For flexible pavements with stabilized bases, the TRRL Kenya[2] results are used. In either case, the traffic composition is converted into standard equivalent axles as follows.

3.5.1 Equivalence Factors

The equivalence factor of an axle is defined as the number of applications of an axle carrying a standard load which would cause the same damage to a road as one application of the axle in question. The standard load used here is 18000 lbs. (8200 kg). The equivalence factors depend, slighly, on the strength of the pavement and its present serviceability index. The equations are:

$$EF = N^{-4.33} \left(\frac{W + N}{18 + 1}\right)^{4.79} \left(\frac{4.2 - PSI}{2.7}\right)^{\alpha} \qquad (3\text{-}1)$$

where EF is the equivalence factor
W is the load in kips on the axle
N is 1 for single axles, 2 for tandem axles

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(1) Highway Research Board, "The AASHO Road Test", Special Report 61E, Publication No. 954, Washington, DC, National Research Council, 1962.

(2) Hodges, J.W., et al. The Kenya road transport cost study: research on road deterioration. Department of the Environment, TRRL Report LR 673. Crowthorne, 1975 (Transport and Road Research Laboratory).

and

$$\alpha = \frac{1}{0.40 + 0.081(18 + 1)^{3.23}(\overline{SN} + 1)^{-5.19}} - \frac{1}{0.40 + 0.81(W + N)^{3.23}(\overline{SN} + 1)^{-5.19}} \tag{3-2}$$

where $\overline{SN}$ is the effective structural number of the pavement.

3.5.2 Effective Structural Number

In the analysis of pavement performance a convenient index of pavement strength is needed. This index must satisfy the condition that two pavements of the same type having the same index will perform identically. The concept of structural number developed during the AASHO Road Test satisfies this requirement, provided that the strength of the subgrade, the impact of the environment, and the drainage characteristics of the base and subbase are incorporated, establishing an effective structural number. The structural number of a pavement is defined by an empirical relationship in which the thickness and strength of each pavement layer are combined together as follows.

$$SN = \sum_{i=1}^{n} a_i D_i \tag{3-3}$$

where a_i is the strength coefficient of the ith layer
D_i is the thickness of the ith layer, in inches and the summation is over all pavement layers

The most satisfactory way of taking into account the strength of the subgrade, the environmental impact, and the drainage characteristics

of the base and subbase is to modify the structural number of the pavement so that it is equal to the structural number of a road of the same type which behaves in the same way but was built in a standard environment on a standard subgrade with standard drainage characteristics. To allow direct comparisons with the AASHO Road Test, the most convenient standards to use are the AASHO conditions themselves, producing the following equation for the effective structural number $\overline{SN}$:

$$(1 + \overline{SN}) = (1 + SN) * (REGFAC * DRNFAC)^{-0.10684} \left(\frac{CBR}{CBR_o}\right)^{0.14744} \qquad (3\text{-}4)$$

where	SN	is the structural number of the pavement
	$\overline{SN}$	is the effective structural number
	REGFAC	is the regional factor (AASHO = 1)
	DRNFAC	is the drainage factor (AASHO = 1)
	CBR	is the CBR of the subgrade
	CBR_o	is the CBR of the AASHO subgrade = 2.69

Equation (3-4) was computed using the graph of soil support vs. CBR reported in the "AASHTO Interim Guide"[1] yielding

$$0.372(S - S_o) \simeq 1.38(\log CBR - \log CBR_o) \qquad (3\text{-}5)$$

where	S	is the soil support of the subgrade
	S_o	is the soil support of the AASHO subgrade (= 3)

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[1] American Association of State Highway and Transportation Officials, AASHTO Interim Guide for Design of Pavement Structures," Washington, DC 1972.

and

$$0.10684 = 1./9.36$$

$$0.14744 = 1.38/9.36 \qquad (3\text{-}6)$$

Higher regional drainage factors indicate weaker effective pavement strengths.

3.5.3 Deterioration of Flexible Pavements with Granular Bases

Paved surface performance for roads with granular bases is analyzed in the model by a routine which simulates the cycle of deterioration and repair. Deterioration is predicted as a function of equivalent axle loads and effective structural number. The equations used to predict this deterioration are of the form of the general AASHO equation, as presented in the "Interim Guide". Deterioration is initially predicted in terms of the AASHO concept of serviceability - PSI. This serviceability measure is related to three measurable characteristics of the surface: slope variance (SV), rut depth (RD), and the amount of cracking and patching (CP) by the equation[1]

$$PSI = 5.03 - 1.91\log_{10}(1 + SV) - 0.01\sqrt{CP \cdot 10} - 1.38RD^2 \qquad (3\text{-}7)$$

Deterioration is predicted as a drop in AASHO serviceability, PSI,

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[1] Carey, W.N., Jr., and Irick, P.E., "Performance of Flexible Pavements in the AASHO Road Test," International Conference on the Structural Design of Asphalt Pavements Proceedings, University of Michigan, 1962.

for each year of the analysis period. The equation for estimating deterioration is the general AASHO equation[1]:

$$PSI(V,\overline{SN}) = 4.2 - 2.7 \cdot (1.58V * (1 + \overline{SN})^{-9.36})^{(0.40+1094(1+SN)^{-5.19})} \tag{3-8}$$

where V is the volume of equivalent standard axles
$\overline{SN}$ is the effective structural number

From this, the deterioration caused by an equivalent traffic volume of ΔV ensuing after a previous total equivalent volume of V would be

$$\Delta PSI(V,\Delta V, \overline{SN}) = PSI(V,\overline{SN}) - PSI(V + \Delta V,\overline{SN}) \tag{3-9}$$

in which ΔPSI is the deterioration due solely to the equivalent traffic volume ΔV.

The model has now been discussed up to the point where the annual deterioration has been computed as a function of the pavement design, traffic, subgrade, regional factor, and drainage factor. Most of the relationships presented were developed from regression analyses of the AASHO Road Test data. The AASHO Test was an accelerated test which lasted approximately two years. As a result, it is likely that very little of the deterioration observed was a result of time dependent variables. To simulate time dependent deterioration, the annual deterioration, ΔPSI, is modified by adding an annual deterioration factor. Since there is little information on the function governing time dependent

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[1] American Association of State Highway and Transportation Officials, "ASSHTO Interim Guide for Design of Pavement Structures", Washington, DC, 1972.

deterioration a constant factor is used to represent this damage:

$$\Delta PSI' = \Delta PSI + AGE \tag{3-10}$$

Thus, the annual drop in PSI is increased by a constant increment each year, independent of traffic damage. It is suggested that this factor be approximately 0.1 units of PSI per year, unless information is available to determine another value.

Another adjustment built into the model allows deterioration to increase with age, as follows:

$$\Delta PSI'' = \Delta PSI' \cdot (1 + I)^{YR} \tag{3-11}$$

where YR is the age of the pavement in years and I is the factor which can be adjusted to local conditions. If no information is available, a value of I from 0.03 to 0.05 is suggested. Thus, we have for the serviceability at any year n, in terms of the previous year's serviceability:

$$PSI_n = PSI_{n-1} - (\Delta PSI + AGE)(1 + I)^{YR(n)} \tag{3-12}$$

Using this new level of serviceability, the degree of deterioration measured in terms of slope variance (SV), rut depth (RD), and amount of cracking and patching (CP) is found using the relationships:[1]

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[1] Highway Research Board, "The AASHO Road Test", Special Report 61E, Publication No. 954, Washington, DC National Research Council, 1962.

$$SV\left(\frac{mm^2}{m^2}\right) = 10^{(0.031PSI^2-0.54PSI+2.3)} - 1 \qquad (3\text{-}13)$$

$$RD(mm) = (-0.03PSI^3 + 0.091PSI + .032) \cdot 25.4 \qquad (3\text{-}14)$$

$$CP(\%) = ((0.3PSI^3 - 1.3PSI^2 - 5.2PSI + 29)^2)/10 \qquad (3\text{-}15)$$

Equations (3-13), (3-14), (3-15) were found by polynomial regression analysis of data collected during the AASHO Road Test. Equations (3-13) and (3-15) 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 (3-13) is 0.91 and the F test indicates that the regression is significant at the 1.0% level. Equation (3-14) 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 (3-14) is 0.61 and the F test indicates signigicance at the 10.0% level. The coefficient of correlation found for Equation (3-15) is 0.68 and the F test indicates significance at the 2.5% level.

The roughness of the road is calculated from the slope variance, assuming a normal distribution of the slopes, to yield:

$$ROUGH(mm/km) = 636.62\sqrt{SV} \qquad (3\text{-}16)$$

3.5.4 Deterioration of Flexible Pavements with Stabilized Bases

The deterioration of pavements with stabilized bases is based on the TRRL Kenya Study, as little additional information is available. Wherever the Kenya data has been found to be unsatisfactory or incomplete, data from other sources have been examined to calibrate their results. All the deterioration relationships included in the model are in the form of polynomial equations relating a surface condition variable to traffic loading for a range of different effective structural number, which are further regressed in terms of the effective structural number.

3.5.5 Surface Roughness

The relationship derived from the Kenya field data by TRRL for surface roughness are:[1]

$$R = R_o + 1500N \text{ for } \overline{SN} = 2.5$$
$$R = R_o + 670N \text{ for } \overline{SN} = 3.0$$
$$R = R_o + 466N \text{ for } \overline{SN} = 3.5$$
$$R = R_o + 365N \text{ for } \overline{SN} = 4.0$$

where R is the roughness (mm/km) measured by a fifth wheel bump integrator towed at 30 km/hr

R_o is the roughness of the road when new (2500) in Kenya

N is the total cumulative traffic loading in millions of equivalent (18kip) axles

These were regressed over $\overline{SN}$ to yield

[1] Hodges, J.W., et al. The Kenya road transport cost study: research on road deterioration. Department of the Environment, TRRL Report LR 673. Crowthorne, 1975 (Transport and Road Research Laboratory.

$$R = 2308\overline{SN}^{\,0.0562} + 9005N * \overline{SN}^{\,-2.287} \qquad (3\text{-}18)$$

3.5.6 Rut Depth

The maximum rut depth reported by TRRL[1] on any of the test sections in Kenya was about 8 mm with the majority of measurements between 3 mm and 5 mm regardless of traffic. The maximum rut depth which is tolerable before reconstruction becomes necessary is usually about 20 mm for this type of pavement; therefore, it is unlikely that failure will occur through excessive rutting. Since TRRL reported no regression for rut depth, we have assigned the function

$$RD(mm) = 3.0 + 10 * N/(\overline{SN}) \qquad (3\text{-}19)$$

where N is the total cumulative traffic loading in millions of equivalent (18kip) axles and $\overline{SN}$ is the effective structural number.

3.5.7 Cracking

The cracking data reported by TRRL[2] were expressed as millions of equivalent standard (18kip) axles to produce a mean cracking of $1m/m^2$ and $3m/m^2$ in the wheeltracks. Their reported values are given in TABLE 3-1.

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[1] Ibid.

[2] Ibid.

TABLE 3-1

Modified Structural Number $\overline{SN}$	Millions of Equivalent Standard Axles	
	$1m/m^2$	$3m/m^2$
2.5	0.24	0.60
3.0	0.60	1.00
3.5	0.85	1.50
4.0	1.40	2.00
4.5*	2.00	2.50
5.0* & above	2.50	----

with local cracking exceeding $5m/m^2$ patched immediately.

Since the present model accepts cracking in square meters per 100 square meters, and since the AASHTO Interim Guide indicates that potholes quickly form whenever the Class 2 cracking exceeds $5m/m^2$, we have assumed that this corresponds to 100% cracking for use in units of square meters/100 square meters.

Thus, the above Table (3-1) data have been curve-fit to yield:

*Estimated by TRRL

$$CP(m^2/100m^2) = 730 * N * \overline{SN}^{-2.754} \qquad (3\text{-}20)$$

where N is the total cumulative standard (18kip) axles in millions
$\overline{SN}$ is the effective structural number
and CP is the percent of surface area cracked or patched.

Serviceability is computed from CP, RD, and SV(R) in the same manner as for granular base roads.

3.6 Maintenance of Paved Roads

Maintenance activities are the same for flexible pavements, regardless of base type, although the component costs may vary depending on surface type. The maintenance activities included in the model for paved surfaces are:

1) routine patching
2) routine sealing
3) seal coating
4) level course
5) overlay

The amount of maintenance work to be done during the year is determined by the deterioration parameters and the maintenance policy specified. Table 3-2 gives a review of the maintenance activities and their units which are included in the model.

3.6.1 Effects of Routine Patching

While patching does not reduce cracking plus patching, it does impact slightly on slope variance and rut depth. The mean slope variance (SV) is partially made up of depressions or potholes which are likely to be repaired by patching, and this reduction (ΔSV_M) is a function of the slope variance and the percent to be patched. The reduction is estimated to be:

$$\Delta SVM = 0.3 \cdot SV \cdot P/100 \qquad (3\text{-}21)$$

where P is the percent patched in this year
ΔSV_m is the reduction in slope variance
SV is the mean slope variance

Further, most of the cracking, and so most of the patching, will be in the wheeltracks. Thus, patching will affect the rut depth also, and since the deeper ruts will tend to be patched first, the mean rut depth will be reduced. This reduction (ΔRD_M) is a function of the rut depth and the percent to be patched, and is estimated to be:

$$\Delta RD_M = 0.55RD \cdot P/100 \qquad (3\text{-}22)$$

3.6.2 Effects of Sealing

Sealing the surface reduces the amount of cracking and patching noticeable on the road surface. This reduction, (ΔCP_M)

$$\Delta CP_M = 0.5CP \cdot A_s \qquad (3\text{-}23)$$

where CP is the cracking and patching
A_s is the fraction of surface area sealed
ΔCP_M is the reduction in CP

3.6.3 Effects for Overlaying

A major overlaying (>2cm) of the road surface restores the serviceability to a value of 4.2, and the age of the pavement to zero. Also, an overlay has an impact on the structural number of the pavement. It is assumed that the overlay is of the same material as the road surface

(else it is a reconstruction), and that the effective structural thickness of the existing surface layer is a function of the amount of cracking and patching, as follows:

$$\overline{D}_1 = D_1(1 - CP/100) + OVRLAY \qquad (3\text{-}24)$$

where OVRLAY is the thickness of the overlay

D_1 is the thickness of the existing surface

CP is the percent of area cracked or patched

$\overline{D}_1$ is the effective structural thickness of the surface after the overlay

3.6.5 Effects on PSI

Once the deterioration parameters have been determined after the maintenance activities, the new serviceability may be computed. However, we have the following inequality to complicate things:

$$PSI_0 \neq PSI(CP(PSI_0), RD(PSI_0), SV(PSI_0)) \qquad (3\text{-}25)$$

This is a result of the regression equations for the deterioration parameters being computed separately, and the recombination to predict PSI is not a one-to-one mapping.

To avoid this non-inverse mapping, we compute the change in serviceability due to maintenance as the difference in the serviceabilities predicted form the deterioration parameters before and after maintenance:

$$\Delta PSI_M = PSI(CP,RD,SV) - PSI(CP - \Delta CP_M, RD - \Delta RD_M, SV - \Delta SV_M) \quad (3\text{-}26)$$

where the parameters are as defined above. The new serviceability is then given by

$$PSI_M = PSI - \Delta PSI_M \quad (3\text{-}27)$$

3.7 Unpaved Roads

There are many combinations of construction materials which are used frequently in highway construction, but which were not studied in the AASHO Road Test or by TRRL in Kenya. As it is not practical to incorporate a large number of deterioration relationships into a computer model, it is the responsibility of the model User to choose that set of relationships described below which most closely approximates the design under consideration.

Most of the deterioration relationships for unpaved roads were derived from the Kenya field data reported by TRRL[1]. Traffic volumes were measured in terms of the total number of vehicles using the road since grading, so no equivalence factors are employed in this part of the model. Also, pavement strength, the essential feature of the paved road deterioration relationships, cannot be used as an index for unpaved roads, because material is constantly being lost from the surface. The roads have therefore been broadly classified according to gravel type or earth type as described below.

The model User normally specifies a blading frequency for unpaved roads, so all deterioration is measured from the time of a blading.

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[1] Ibid.

3.8 Deterioration of Gravel Roads

The essential requirement of gravel roads is that they be properly engineered with adequate drainage. The deterioration rates used in the model will certainly not apply if these conditions are not met. It is assumed that gravel roads are passable during the whole year.

3.8.1 Surface Roughness

Traffic volume and gravel type were found to be the most important determiners of surface roughness. Two relationships are used within the model to predict surface roughness:

$$R = 3250 + 84T - 1.62T^2 + 0.016T^3 \qquad (3\text{-}28)$$

for lateritic, quartzitic, and volcanic gravels

$$R = 6500 + 58T - T^2 + 0.017T^3 \qquad (3\text{-}29)$$

for coral gravels.

where R is the mean roughness measured in the wheel tracks in mm/km by a fifth wheel bump integrator towed at 30 km/hr

T = cumulative traffic volume in both directions which has used the road since blading, measured in thousands of vehicles.

Equation (3-28) was derived from data which extended to a traffic loading of approximately 100,000 total vehicles and a roughness value of approximately 14,000 mm/km, whereas equation (3-29) was based on data which extended to a traffic loading of approximately 45,000 vehicles and a roughness about 10,000 mm/km, which TRRL extrapolated to the roughness level as equation (3-28)[1].

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[1] Ibid.

The model User must specify a grading frequency (either bladings/ month or 1000's of vehicles/blading), and the model then calculates the mean roughness of the road at that frequency. This result is then used in the calculation of road user costs, and the grading frequency itself partly determines the total maintenance costs.

3.8.2 Rutting

Traffic volume and gravel type were again found to be the most important variables influencing rutting. The relationships used with the model to predict rutting are:

$$RD = 11 + 0.23T - 0.0037T^2 + 0.000073T^3 \qquad (3\text{-}30)$$

for lateritic gravel pavements

$$RD = 17.5 + 0.73T \qquad (3\text{-}31)$$

for volcanic, quartzitic and coral gravel pavements

where RD is the rut depth in mm under a 2m straight edge

T is the cumulative traffic volume in both directions which has used the road since grading, measured in thousands of vehicles.

Equation (3-30) was derived from data which extended a total traffic loading of approximately 100,000 vehicles and a rut depth of about 70mm, while Equation (3-31) was derived from data which extended a traffic loading of approximately 45,000 vehicles and a rut depth of about 60mm.[1] The model calculates the mean rut depth between gradings in the same way as the mean roughness was calculated.

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[1] Ibid.

3.8.3 Surface Looseness

Two relationships from the Kenya data have been incorporated into the model:

$$LD = 5 * e^{-.35T} + 1.5 \qquad (3\text{-}32)$$

which is used for all gravel types graded in a wet condition.

$$LD = 14 * e^{-.23T} + 1.5 \qquad (3\text{-}33)$$

which is used for all gravel types graded in a dry condition.

where LD is the depth of loose material, in mm

T is the cumulative traffic volume in both directions using the road since the last grading, in thousands of vehicles

The model uses the above information to calculate the mean looseness between each grading.

3.8.4 Gravel Loss

The quantity of gravel lost from the pavement surface depends on annual rainfall, traffic volume, traffic speed, gravel type and road geometry. It was not possible for the TRRL Kenya study to quantify the effects of traffic speed and road geometry, but they produced a single equation relating the other variables[1], which has been incorporated into the model:

$$GL_A = F(\text{gravel type}) \frac{8 + 3RL^2 + 0.1T_A}{1 + 50/T_A^2} \qquad (3\text{-}34)$$

where GL_A is the annual gravel loss, in mm

RL is the annual rainfall, in meters

T_A is the annual traffic volume in both directions, in thousands of vehicles

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[1] Ibid.

F is a function of gravel type and has the value of 1.0 for lateritic and quartzitic gravels, 0.7 for volcanic gravels, and 1.4 for coral gravels.

TRRL also concluded that frequency of grading had no noticeable effect on annual gravel loss.

3.9 Deterioration of Earth Roads

The relationships used in the model to estimate the deterioration of earth roads are extremely rough approximations, and caution should be exercised whenever the predicted benefits associated with upgrading an earth road to a gravel road are small.

The data obtained in Kenya only extended to a traffic loading of 20,000 vehicles, and none of the test sections were impassable at that point. However, the model user may specify the number of months per year for each of three seasons: the dry season, when earth and gravel surfaces are dusty; the wet season, when earth and gravel surfaces are not dusty, and the impassable season, when earth roads are not serviceable, but gravel roads are. Also, the User must specify the frequency of grading in the wet and dry seasons.

3.9.1 Surface Roughness

The TRRL Kenya study produced no general relationship between roughness and cumulative traffic loading, so the relationships used previously in the Highway Cost Model have been retained. This is:

$$R = 3156 + 631T \qquad (3\text{-}35)$$

where R is the mean roughness, in mm/km

T is the cumulative traffic volume in both directions which has used the road since grading in thousands of vheicles

3.9.2 Rutting

TRRL applied linear regression to all rut depth measurements and derived the following equation[1], which has been incorporated into the model:

$$RD = 14 + 1.4T \qquad (3\text{-}36)$$

where RD is the rut depth in mm under a 2m straight edge

T is the cumulative traffic volume in both directions which has used the road since grading, in thousands of vehicles

3.9.3 Surface Looseness

The same equations are used in the model to estimate the depth of loose material for both earth and gravel roads.

3.10 Maintenance of Unpaved Roads

As previously mentioned, the maintenenace of unpaved road surfaces is primarily surface grading. This may be specified by the User to be either gradings/month or thousands of vehicles/grading. The volume of traffic using the road between gradings then determines the mean surface conditions.

Spot regravelling may also be done on gravel roads to repair areas

[1] Ibid.

of severe gravel loss. This may be specified by the User to be either cubic meters/kilometer/year or cubic meters/kilometer/thousand vehicles. The surface thickness is then increased, depending on the total volume of material placed.

Gravel resurfacing may also be specified by the model User, as either years between regravellings or minimum tolerable surface thickness, together with the desired surface thickness after regravelling. The volume required to produce this desired surface thickness is then calculated by the model.

3.10.1 Shoulder Maintenance

The shoulders of a paved road may be either paved or unpaved, for which different routines have been incorporated within the model. Maintenance for paved shoulders is estimated either as user specified quantities per year, or as a function of the amount of maintenance performed on the riding surface and the width of the riding surface (see Table 3-2).

If the shoulder is unpaved, the maintenance cost is estimated either from user specified frequencies and quantities, or as a function of traffic volume and road width. Again, see Table (3-2) for the detailed activities which the model can perform.

3.11 Maintenance Requirement for Both Paved and Unpaved Roads

3.11.1 Drainage Maintenance

The cost of drainage maintenance is estimated from the amount of sediment deposited in the ditches and drainage structures during the year. This is a function of rainfall, type of terrain, and steepness of the cut and fill slopes, which were the parameters that could be found in the literature affecting the amount of sediment deposited. It seems

reasonable to assume that type of soil, ground cover, and land use also play an important role in how much sediment is deposited. However, no information could be found about the effect of these variables that could be used to establish this relationhsip. This may, therefore, be a case where a modest amount of research could produce information of value to maintenance prediction in an area now nearly vacant. The equation used for the amount of sediment deposited is

$$S_A = 6 + 3(1 + RL_A) \cdot TF \cdot SSF \qquad (3\text{-}37)$$

where S_A is the amount of sediment deposited annually per kilometer, in cubic meters

RL_A is the annual rainfall, in meters

TF is the terrain factor

a. mountainous = 1.0

b. rolling = 2.0

c. flat = 3.0

SSF is the side slope factor

$$SSF = 0.5 + (1/\text{cut slope}) + (1/\text{fill slope}) \qquad (3\text{-}38)$$

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 deposited sediment. The effect of blocked drains and culverts on the deterioration of the road is not predicted.

3.11.2 Vegetation Control

Vegetation control is not usually a major part of maintenance cost. Therefore, the routine which 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 frequency of mowings is specified by the model user, either as mowings/year of rainfall/mowing. The amount of labor, equipment, and materials required is then estiamted by the model.

3.12 Maintenance Policy Options

A maintenance policy consists of a frequency schedule for all maintenance activities to be performed. Only those activities applicable to the pavement type being analyzed will be considered. Thus, for example, bladings will not be considered for paved roads. Up to five maintenance policies may be specified in the model, each of which may be applied for any or all years of the analysis period. The following is a description of the maintenance activities which the model performs.

3.12.1 Maintenance Activities

The model has incorporated twenty-four maintenance activities into its structure, each of which may be scheduled or responsive. Scheduled maintenance activities are done at specific times, regardless of the state of roadway deterioration; while responsive maintenance activities are done when the roadway has deteriorated to a specific condition, regardless of the time at which that condition is reached. These capabilities, coupled with the option of five different policies, provide a powerful range of maintenance analysis. TABLE 3-2 gives an explanation of the twenty-four activities, and their scheduling options.

3.13 Maintenance Costs

The direct costs of maintenance in each year are estimated based on the amounts of maintenance performed and appropriate unit costs. These unit costs reflect direct expenditures for skilled and unskilled labor, equip-

TABLE 3-2 MAINTENENCE ACTIVITIES AND QUANTITIES

(S = Scheduled maintenance R = responsive maintenance)

1. Surface grading of earth roads--dry season
   S = gradings/month R = 1000 vehicles/grading

2. Surface grading of earth roads--wet season
   S = gradings/month R = 1000 vehicles/grading

3. Surface gradings of gravel roads--dry season
   S = gradings/month R = 1000 vehicles/grading

4. Surface grading of gravel roads--wet season
   S = gradings/month R = 1000vehicles/grading

5. Spot regravelling of gravel roads
   S = cubic meters/km/year R = cubic meters/km/1000 vehicles

6. Gravel resurfacing of gravel roads*
   S = years cycle time R = minimum allowable thickness

7. Surface patching of bituminous surface roads
   S = square meters/km/year R= % cracks to be patched

8. Surface patching of asphalt concrete surface roads
   S = square meters/km/year R = % cracks to be patched

9. Routine sealing of bituminous surface roads
   S = square meters/km/year R = % cracks to be sealed

10. Routine sealing of asphalt concrete roads
    S = square meters/km/year R = % cracks to be sealed

11. Seal coating of entire bituminous surface*
    S = years cycle time R = maximum % cracking allowable

12. Seal coating of entire asphalt concrete surface*
    S = years cycle time R = maximum % cracking allowable

13. Levelling course for bituminous surface road*
    S = years cycle time R = maximum % cracking allowable

14. Levelling course for ashpalt concrete roads*
    S = years cycle time R = maximum % cracking allowable

15. Overlyaing of entire bituminous surface*
    S = years cycle time R = minimum PSI allowable

TABLE 3-2 (cont'd)

16. Overlaying of entire asphalt concrete surface*
    S = years cycle time R = minimum PSI allowable

17. Grading of gravel shoulders on paved roads
    S = gradings/year R = ADT/grading

18. Resurfacing of gravel shoulders on paved roads
    S = cubic meters/km/year R = cubic meters/km/1000 vehicles

19. Brush and vegetation control
    S = times/year R = rainfall (mm)/time

20. Culvert and ditch cleaning
    S = times/year R = rainfall (mm)/time

21. Patching of bituminous shoulders
    S = square meters/km/year R = % of roadway patching

22. Patching of asphaltic concrete shoulders
    S = square meters/km/year R = % of roadway patching

23. Resurfacing of bituminous shoulders
    S = cubic meters/km/year R = only with overlay

24. Resurfacing of asphalt concrete shoulders
    S = cubic meters/km/year R = only with overlay

*Indicates that action will be performed when either condition is met. Thickness of resurfacing must also be specified.

ment, and materials, and are specified as shown in TABLE 3.3. Since maintenance expenditures tend to be a fairly small percentage of total transport costs, no attempt has been made to provide a finer breakdown of costs, or to account separately for the production and the transport of materials, as may be done in the computation of construction costs.

Indirect costs are estimated as a percentage of total direct costs.

If desired, maintenance expenditures may be provided for selected years on a segment by segment, activity by activity basis as shown in TABLE 3.4.

3.14 Summary

The relationships used in the maintenance-deterioration model have been based primarily on field studies conducted by AASHC and TRRL, and on information found in the engineering literature. Unfortunately, some of the relationships are not well supported or are applicable only within certain limits. Where little could be found about the nature of a needed relationship, logic, and judgement 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 predicted behavior has been generally realistic for the range of situations studied.

However, until further research more accurately establishes the nature of these relationships, the limitations on the accuracy of the model should be recognized. The present model provides a conceptually sound

framework which can easily be modified to incorporate the additional information to be developed by future research.

IV. VEHICLE OPERATING COSTS AND TRAFFIC

4.1 Introduction

This chapter describes the methods used to estimate vehicle operating costs and to predict the amount of traffic using the road; Operating costs reflect the geometric standards to which the road was constructed; the type of surface; and the current surface condition as determined through the interaction of pavement design, environment, maintenance policy and the volume and mix of traffic. Operating costs are estimated by first determining the amount of resources consumed in vehicle operation, and by then applying appropriate factor prices.

Traffic volumes are estimated by applying either percentage or incremental growth factors to the previous years traffic to arrive at a preliminary estimate for the current year. This estimate is used in maintenance-deterioration submodel to predict road surface conditions, which in turn are reflected in operating costs. These operating costs are then used to adjust the preliminary estimate of traffic in accordance with demand elasticities.

The output from the submodel consists of vehicle operating costs for the year, broken down by type of vehicle and cost category; and a final estimate of traffic volumes for each type of vehicle.

4.2 Data Requirements

The data requirements of the submodel consist of road geometry; surface type and condition; vehicle characteristics and costs; and base traffic projections. The specific variables required are as follows:

4.2.1 Road Geometry

Road geometry is specified in terms of the rise and fall of the road (m/km), horizontal curvature (°/km), and road width (m). These variables reflect the geometric standards of the road, as it exists in the current

year, and have been discussed in the chapter on road construction.

4.2.2 Surface Type and Condition

Surface type is either unpaved (earth or gravel) or paved (bituminous treated or ashpalt concrete). Surface conditions, discussed previously in the chapter on road deterioration and maintenance, and described in terms of surface roughness and rut depth for all roads and, in addition, surface moisture and looseness for unpaved roads.

4.2.3 Vehicle Characteristics and Costs

The traffic using the road may be represented by up to seven different types of vehicles. The required characteristics of each of these representative vehicles are summarized in TABLE 4-1 and salient points are discussed below.

Vehicle Classification: Each representative vehicle is classified into one of five categories as shown in TABLE 4-2. These categories correspond to the major categories of vehicles studied by TRRL and are the ones for which separate resource consumption equations were developed.

Vehicle categories provide major breaking points between different classes of vehicles. Within a category, however, representative vehicles must be further differentiated according to their specific payloads, horsepower axle loading, etc.

Design Speed: The design speed, specified in kilometers per hour, is the efficient cruise speed of the vehicle on a level, tangent paved road under uncongested conditions. Where possible, this figure should be based on actual observations of driver habits, since this speed is used as an upper limit on the speed of the vehicle.

TABLE 4-1

REPRESENTATIVE VEHICLE CHARACTERISTICS

Physical Descriptions	Coding or Units
1. Vehicle Classification	integer, see Table 4-2
2. Fuel Type	1=gas, 2=diesel
3. Tare Weight	metric tons
4. Maximum Payload	metric tons
5. Horsepower	BHP
6. Design Speed	kilometers per hour*
7. Axle Configuration and Loading	*
Price Descriptors (in currency of analysis)	
8. Cost of New Vehicle (Financial & Economic	per vehicle
9. Tire Cost (Financial & Economic)	per tire
10. Fuel Cost (Financial & Economic)	per litre
11. Oil Cost (Financial & Economic)	per litre
12. Overhead (Financial & Economic)	annual
13. Insurance (Financial & Economic)	annual
14. Registration & Licensing (Financial Only)	annual
15. Driver Wages (Financial & Economic)	per month
16. Helper(s) Wages (Financial & Economic)	per month
17. Maintenance Labor Wage (Financial & Economic)	per hour
18. Value of Time (Financial & Economic)	per hour
19. Financial Discount Rate	percent
20. Economic Discount Rate	percent
21. Parts Price Ratio	*
22. Annual Average Distance Utilized	kilometers per year
23. Annual Average Hours Utilized	hours per year*
24. Depreciable Lifetime	years

TRAFFIC CHARACTERISTICS

Volumetric Descriptors	
1. Base ADT	**
2. Load Factor--Outbound & Inbound	**
3. Rate(s) of Growth	**
4. Price Elasticity	**

*See text of 4.2.3
**See text of 4.2.4

TABLE 4-2

VEHICLE CLASSIFICATION SCHEME

	TYPE OF VEHICLE	
1	Motor Cars	This class includes passenger vehicles seating not more than nine persons (including the driver). Estate cars, taxis, and hire cars are generally included but not "Land Rover" type vehicles or mini-buses.
2	Light Goods	Goods vehicles of less than 1500kg. Unladen weight or vehicles with a payload capacity of less than 760 kg. This class specifically includes "Land Rover" type vehicles and mini-buses.
3	Buses	This class consists of all regular passenger service vehicles and coaches.
4	Medium Goods	This class includes all 2 axled goods vehicles of more than 1500kg. Unladen weight or vehicles with a payload capacity greater than 750kg. In general medium goods vehicles differ from light goods vehicles in that they have more than one tyre at each end of the rear axle, i.e. twin-tyres. The maximum gross vehicle is 8.5 metric tons.
5	Heavy Goods	This class consists of all goods vehicles with more than two axles and is often sub-divided into groups with specific axle configurations. Also involved are two axle vehicles with gross vehicle weight over 8.5 metric tons.

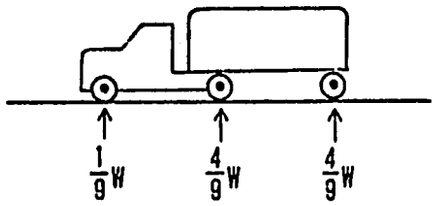
Axle Configuration and Loading: The road deterioration caused by a vehicle is a function of the number, type, and percent load of each axle group. Axle type is either single or tandem (two closely spaced axles) and the percentage load is based on the weight distribution of the vehicle in the fully loaded (but not overloaded) condition.

Where actual axle loadings are not available a simple methodology for computing the axle loads is recommended by Lago.[1] A fraction is established for each axle group where the denominator is (N - 1), where N is the total number of tires. The numerator for the front axle is 1, and for all others it is the number of tires in the axle group. A simple calculation is shown in Figure 4-1.

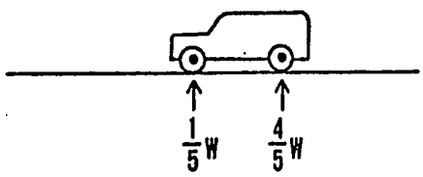
Value of Time: Improvement in a road often results in a reduction in travel time. In addition to freeing the vehicle for other uses, there are often benefits to be gained from reducing the amount of time that the cargo is in transit. These benefits may be quite large in the case of perishable food stuffs, but will generally be less significant for durable goods, and for cargo that will be stored for several days after unloading. The time value is expressed as an hourly rate, and is the benefit which is gained for a unit decrease in travel time from the existing road. This time value may have both financial and economic components.

Parts Price Ratio: This factor permits conversion of the financial cost of the spare parts required for vehicle maintenance to an economic cost. This ratio may differ from the ratio of the economic to the financial cost of the new vehicle because of differences in the duty rates and other taxes on assembled vehicles versus spare parts. The ratio

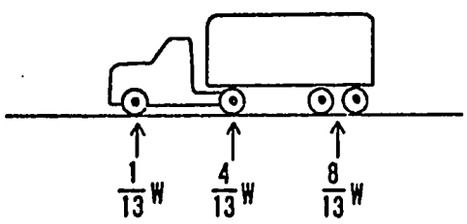
[1] Lago, A.M., Cost Functions for Intercity Transport Systems... after Baker, R.F. et al, "Highway Costs and Their Relationship to Vehicle Size" Engineering Experiment Station Bulletin 168, Ohio State University, March 1958, p. 53.



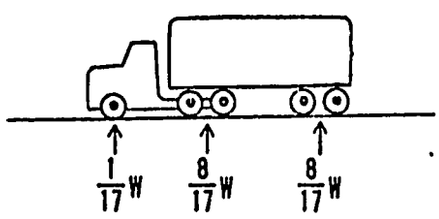
TYPE I: Tractor Semi-trailer
Single Axles
Ten tires



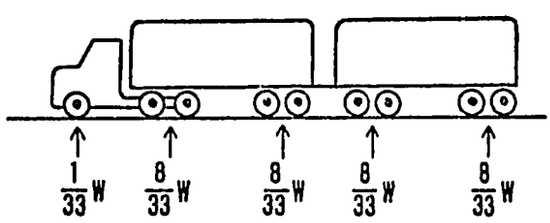
TYPE II: Single Unit Truck
Single Axles
Six tires



TYPE III: Tractor Semi-trailer
Single Axles in Tractor
Tandem Axles in Semi-Trailer
Fourteen tires



TYPE IV: Tractor Semi-trailer
Single Axle in front of Tractor truck
Tandem Axle type in the other axles
Eighteen tires



TYPE V: Tractor Semi-trailer and full trailer
Single Axle in front of tractor truck
Tandem Axle type in the other axles
Thirty-four tires

NOTE: Except in the front axle, all trucks have dual tires.

SOURCE: Robert F. Baker, Robert Chieruzzi, Richard W. Bletzacker, *Highway Costs and their Relationship to Vehicle Size*, Engineering Experiment Station, Bulletin 168, (The Ohio State University, March 1958), p. 53.

FIGURE 4-1 TYPES OF AXLE DESIGNS

may be computed as:

$$\text{Parts Price Ratio} = (1 + \text{Spare parts tax ratio})^{-1}$$

Annual Average Hours Utilized: This figure reflects the number of hours that the vehicle is actually driven in a year. Assuming 2080 work hours in a year (40 hours/week), the actual utilization may be on order of 1500 or 1600 hours for trucks, after allowing for repairs and loading operations.

4.2.4 Traffic Projections

Estimates [illegible] traffic volumes and traffic growth characteristics must be p[illegible] each type of vehicle using the road. The specific variables [illegible] required are summarized in Table 4.1 and are discussed below.

Base ADT: The average daily traffic (ADT) for each type of vehicle must be estimated for the base year of the analysis. These volume figures are the total for travel in both directions with an assumed 50-50 directional split.

Load Factor--Outbound and Inbound: The load factor is the percentage of the maximum payload that is actually being carried by the vehicle. Overloading is indicated by numbers greater than one. This number must be specified for each type of vehicle and for each direction. By convention the outbound direction is the direction of increasing stations.

The load factor is used in the calculation of gross vehicle weight, which is in turn used to estimate the fuel consumption and tire wear components of vehicle operating costs, and the damage due to traffic in the pavement deterioration relationships.

Traffic Growth Patterns: Growth of traffic above the base ADT is estimated annually for each type of vehicle. The growth rate can be specified on either an incremental or percentage basis and may be changed during analysis period.

Price Elasticity: The volumes of traffic estimated using the above growth rates are preliminary estimates which are used to estimate pavement conditions and, in turn, user costs. The final estimates of traffic will in addition reflect changes in the costs of operating vehicles over the road on a year to year basis. When costs increase, there may be some reduction in the volume of traffic, and vice versa. The rate at which traffic volumes respond to changes in costs is termed the elasticity of demand, and it must be provided for each type of vehicle.

4.3 Costs of Operation

Vehicle operating costs are a function of road geometry, surface type and condition, and the characteristics of the vehicles using the road. Because road grades and vehicle payloads may be different in each direction, the costs of vehicle operation per kilometer are computed for both directions of travel and averaged. In addition, because surface conditions on unpaved roads may vary on a seasonal basis, the costs of operating on unpaved roads are computed for each season and weighted by the season length to produce the average cost per kilometer.

The surface conditions used in the vehicle operating cost relationships represent the average conditions for the season (unpaved roads) or year (paved roads).

Costs are calculated in three main categories:

A. Running Costs
B. Annual Fixed Costs
C. Time Value of Cargo

Running costs are those costs incurred through operation of the vehicle and include fuel, oil, tires, maintenance parts and maintenance labor.

Annual fixed costs are basic ownership costs and are incurred whether the vehicle is used or left standing idle for the entire year. These costs include depreciation, overhead, registration and licensing, driver(s) and helper(s) wages, and interest charges.

The time value of cargo, as explained previously, represents the benefits to be obtained from reducing the time that cargo is in transit.

Costs are computed in both financial and economic terms. Financial costs represent the actual costs incurred by the owner in operating vehicles over the road. Economic costs represent the real costs to the economy of undertaking that activity.

The various components of vehicle operating costs are summarized in Table 4.3. The specific procedures used to estimate these costs are described below, following a discussion of vehicle speed and age.

4.3.1 Vehicle Speed

The average operating speeds of vehicles using the road are needed in order to estimate fuel consumption and travel times, which are in turn required to apportion the annual fixed costs and to determine the value of time savings.

The speed prediction relationships used in the Highway Cost Model are based on the work of TRRL in Kenya, and have been developed from 130,000 observations of speeds for different vehicle types, road geometries and

TABLE 4-3

	Financial	Economic
A. Running Costs		
1. Fuel	Yes	Yes
2. Oil	Yes	Yes
3. Tires	Yes	Yes
4. Maintenance Parts	Yes	Yes
5. Maintenance Labor	Yes	Yes
B. Annual Fixed Costs		
6. Depreciation	Yes	Yes
7. Overhead	Yes	Yes
8. Insurance	Yes	Yes
9. Registration and Licensing	Yes	No
10. Driver(s) & Helper(s) Wages	Yes	Yes*
11. Interest Charges	Yes	No
C. Time Value of Cargo		
12. Value of Time	Yes	Yes

*Normally helpers in LDC's are from surplus labor pools and attract no economic cost.

surface conditions over a two year period[1]. These relationships are of the following general form:

SPEED = f(RISE, FALL, CURVATURE, ALTITUDE, WIDTH, ROUGHNESS, MOISTURE, RUT DEPTH)

The relationships do not account for vehicle interaction from congestion and speed cycle changes, but do reflect the small effects of reduced road width.

The TRRL equations were developed for passenger cars, light goods vehicles, medium and heavy goods vehicles, (in one category), and buses on both paved and unpaved roads.

On unpaved roads, TRRL found that all variables but altitude had a significant affect on vehicle speeds. The actual coefficients for TRRL's multiple linear regression analysis are shown in TABLE 4-4. The affects of road width are accounted for in a separate equation as shown.

On paved roads, TRRL found that rise, fall, curvature, altitude and width were significant over the range of surface conditions studied. (Roughness less than 4500mm/km). In particular, they found that the coefficient for roughness was insignificant and of the wrong sign, and it was therefore dropped from their equations. TRRL did not study the affects of roughnesses higher than 4500mm/km on their road test sections because this value corresponded to a failed condition.

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[1] Hide, H. et al, The Kenya road transport cost model: research on vehicle operating costs. Department of the Environment, TRRL Report LR 672. Crowthorne, 1975 (Transport and Road Research Laboratory).

TABLE 4-4. COEFFICIENTS FOR SPEED EQUATIONS PLUS LOWER LIMITS OF SPEED

	α_0 (Constant)	α_1 Rise	α_2 Fall	α_3 Curvature	α_4 Altitude	α_5 Roughness	α_6 Moisture	α_7 Rut Depth	α_8 (Width)	α_9 Minimum Speed
1. Passenger Cars										
Paved	102.62	-0.37243	-0.06613	-0.09633	-0.00428	-0.00311	N/A	N/A	7.31	20.0
Unpaved	84.19	-0.20947	-0.06977	-0.11812	N/A	-0.00089	-0.13481	-0.18584	4.32	20.0
2. Light Load Commercial										
Paved	86.88	-0.36013	-0.04274	-0.06353	-0.00239	-0.00284	N/A	N/A	7.31	10.0
Unpaved	81.23	-0.31708	-0.05925	-0.09664	N/A	-0.00095	-0.29296	-0.19657	4.32	10.0
3. Buses										
Paved	72.50	-0.45716	+0.05745	-0.05750	-0.00363	-0.00321	N/A	N/A	3.29	5.0
Unpaved	62.97	-0.49172	+0.01022	-0.04628	N/A	-0.00036	-0.016327	-0.09054	6.36	5.0
4. Medium & Heavy Load Commercial										
Paved	68.06	-0.46405	+0.02673	-0.05193	-0.00037	-0.00209	N/A	N/A	3.29	5.0
Unpaved	69.26	-0.43342	+0.00445	-0.06098	N/A	-0.00060	-0.22111	-0.26535	6.36	5.0
Variable Units	—	meters/km	meters/km	degrees/km	meters	mm/km	%	mm	meters	km/hour
Safe Range of Variable Validity										
Paved	—	0-85	0-85	0-200	0-25	1500-4500	—	—	—	—
Unpaved	—	0-80	0-80	0-250	—	2000-14000	0-30	0-75	—	—

General Form of Equations

$$\text{SPEED} = \alpha_0 + \alpha_1 \text{RISE} + \alpha_2 \text{FALL} + \alpha_3 \text{CURVATURE} + \alpha_4 \text{ALTITUDE} + \alpha_5 \text{ROUGHNESS} + \alpha_6 \text{MOISTURE} + \alpha_7 \text{RUT DEPTH}$$

If road width is less than 5.0 meters,

$$\text{SPEED} = \alpha_8 (5.0 - \text{ROAD WIDTH})$$

If speed is less than minimum,

$$\text{SPEED} = \text{MINIMUM}$$

The finding that road roughness has an insignificant impact on speeds runs counter to the prevailing thought in this area, and , if true, is a significant finding. However, because of certain reservations about the way the TRRL analysis was done, MIT has modified the TRRL equations to reintroduce this factor, pending further clarification. The resulting equations are shown in TABLE 4-4.

In countries where cruising speeds on level tangent paved roads are less than those implied in the TRRL equations, the maximum cruising speed is used as the upper limit on speed for each type of vehicle. An arbitrary lower limit is also provided, which roughly corresponds to operating speeds on the lowest quality earth roads which are still passable.

4.3.2 Vehicle Age Spectrum

The age distribution of vehicles using a road affects the maintenance, depreciation and financing charges. One aspect of TRRL's work was therefore to develop a fleet age distribution function for the Kenya vehicle fleet.

While the form of this function is generally applicable, the data base on which the function is based is solely Kenyan, and as such can be said to model only the Kenyan situation. Since no generally valid function is available, the Highway Cost Model assumes uniform average aging for all vehicles. This means that all vehicles of the same type are assumed to be (a) the same age and (b) that is equal to one-half the normal span of that type of vehicle.

The consequences of this assumption are as follows: in an expanding economy, the rate of vehicle replacement is greater than one, i.e., more vehicles are entering the national fleet than are being retired. In this case, the average age is less than half and the assumption will predict lower depreciation, lower finance charges and higher maintenance

than would be predicted in a methodology using an accurate age distribution function. As the rate of economic growth levels, the average age of the vehicle fleet approaches the average age assumed and the results are consistent between the two methodologies. If import restrictions are placed on vehicles, then the HCM assumption will predict lower maintenance and higher depreciation and finance costs than would be expected for the fleet which would now have an average age greater than one-half.

It is not expected, however, that the error generated by this assumption will place the total results outside the range of accuracy acceptable for feasibility level studies.

4.3.3 Running Costs

Running costs consist of those costs which are incurred as a direct result of vehicle operation. They include the costs of fuel, oil, tires, and maintenance parts and albor. Generally speaking, they vary with vehicle class and age, surface type (paved and unpaved) and condition design geometry, vehicle speed, and driver habits. The major source of new primary data on resource consumption relationships for the various components of runnnng costs is the TRRL Kenya Study. Although the study was not complete in every respect, it serves as the primary source for the relationships used in the Highway Cost Model. The specific components of running costs are computed in the following manner.

Fuel: The general form of the fuel consumption relationships used in the model is

$$\text{FUEL} = \text{FUEL TYPE} * \text{PR}$$

where

$$\text{PR} = f(\text{SPEED, RISE, FALL, ROUGHNESS, GVW, PWR})$$

with PR = Power requirement

GVW = Gross vehicle weight

PWR = Power to weight ratio $(\frac{\text{horsepower}}{\text{GVW}})$

Those equations were developed by TRRL using multiple linear regression techniques on the results of experiments conducted on (1) passenger cars using a Ford Cortina estate wagon, (2) light goods vehicles using a Land Rover, and (3) buses and (4) medium and heavy goods vehicles using a 7 ton Bedford diesel truck and a varying payload. These equations are shown in TABLE 4-5 for both paved and unpaved roads.

Since the fuel consumption data for buses and medium and heavy goods vehicles were all obtained using the Bedford lorry, the experimental results were compared by TRRL with survey data and corrected to those found shown in Table 4.5. This was done by incorporating a power to weight ratio into the relationships as shown.

The fuel consumption relationships for medium and heavy trucks also reflect the fact that all trucks in Kenya are diesal fueled. Since trucks in other countries can also be gasoline fueled, MIT has introduced a fuel type factor into the analysis. For uniformity this fuel factor has been applied to all equations. These factors (gasoline [petrol]= 0.085; diesel fuel = 0.05) reflect the quantity of fuel in litres required to produce a given unit of horsepower [1]. This fuel factor is α_{10} in the general power requirement equation (TABLE 4-5). The power requirement is then multiplied by the actual fuel factor of the vehicle to give the fuel consumption in litres per 1000 kilometers. Fuel is divided by 1000 and multiplied by the financial and economic costs per litre of the appropriate fuel to give the financial and economic costs of fuel per vehicle-kilometer.

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[1] Guenther, K.W., "Predictive Models for Vehicle Operating Consequences", Research Report P69-2, Department of Civil Engineering, MIT, January 1969.

TABLE 4.5 COEFFICIENTS FOR FUEL CONSUMPTION EQUATIONS

	α_0 (Constant)	Speed α_1	Speed α_2	Rise α_3	Fall α_4	Roughness α_5	Looseness α_6	GVW α_7	BHP/GVW α_8	Upwards Adjustment Multiplier α_9	Fuel Factor α_{10}
1. Passenger Cars											
Paved	53.36	+ 498.6716	+0.0058	+1.5936	-0.8539	≠	N/A	N/A	N/A	1.08	0.085
Unpaved	46.90	+ 614.0449	+0.0079	+1.7235	-1.0657	+0.0011	+0.8218	N/A	N/A	1.08	0.085
2. Light Load Commercial											
Paved	74.70	+1150.5088	+0.0131	+2.9058	-1.2774	≠	N/A	N/A	N/A	1.08	0.085
Unpaved	72.78	+ 844.2944	+0.0137	+2.8283	-1.3062	+0.0011	+1.7565	N/A	N/A	1.08	0.085
3. Medium Load Commercial											
Paved	105.43	+ 902.5266	+0.0143	+4.3616	-1.8335	≠	N/A	N/A	-2.3955	1.13	0.050
Unpaved	121.99	+ 795.8916	+0.0150	+4.1760	-2.2163	+0.0014	+1.9688	N/A	-2.6192	1.13	0.050
4. Buses & Heavy Load Commercial											
Paved	- 48.57	+ 902.5266	+0.0143	+4.3616	-1.8335	≠	N/A	+69.2	-2.3955	1.13	0.050
Unpaved	- 32.01	+ 795.8916	+0.0150	+4.1760	-2.2163	+0.0014	+1.9688	+69.2	-2.6192	1.13	0.050
Variable Units	—	km/hr	km/hr	m/km	m/km	mm/km	mm	MT	HP/MT	—	—
Safe Range of Variables											
Paved	—	see limits as defined in Table 4-4		0-85	0-85	—	—	3.5-24.0	40:1-5:1	—	—
Unpaved	—			0-80	0-80	2000-14000	0-20	3.5-24.0	40:1-5:1	—	—

General Form of Equation

$$FUEL = ((\alpha_0 + \alpha_1/SPEED + \alpha_2 SPEED^2 + \alpha_3 RISE + \alpha_4 FALL + \alpha_5 ROUGHNESS + \alpha_6 LOOSENESS + \alpha_7^2/GVW + \alpha_8 \frac{POWER}{GVW}) * \alpha_9) + \alpha_{10}$$

≠ See TABLE 4-6

For paved roads add:

FUEL = FUEL * MULT

where MULT is Claffey Roughness Multiplier

On unpaved roads, TRRL was able to relate two surface condition variables--roughness and looseness--to fuel consumption. However, for paved roads, surface conditions did not affect fuel consumption within the range of conditions studied. In order to extend this analysis to include roughness, the Highway Cost Model incorporates relationships developed by Claffey[1]. These relationships are in the form of a matrix which provides fuel consumption multipliers for speed between 16 and 80 km/hr and roughness between 1800 and 5000 mm/km for all vehicle classes, save heavy goods commerical trucks. The multiplier outside these ranges is unity. The matrix is shown in TABLE 4-6.

Oil: The consumption of oil represents about 1% of the total cost of vehicle operation and as such, there has been very little research in relating the oil consumption rates to either geometry or surface condition. Prior to the Kenya Study, oil had been calculated as function of speed and road type. TRRL was unable to verify that such a speed relationship existed and found instead that a fixed consumption per 1000 km for unpaved and paved roads was sufficient. Because the earlier functions are seriously out of date, the HCM has used the TRRL relationships even though they do not relate oil consumption to either the geometry or surface condition, particularly roughness. The oil consumption rates are shown in TABLE 4-7. Oil consumption costs per kilometer are calculated from consumption in the same manner as those of fuel. Oil prices are for one grade only.

Tire Wear: From their survey of operators, TRRL was able to develop two equations for estimating time wear. For passenger cars and light good commercial vehicles, they found that

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[1] Claffey, P.J., Running Costs of Motor Vehicles as Effected by Road Design and Traffic, NCHRD Report 111, Washington, DC 1971.

TABLE 4-6

CLAFFEY's MULTIPLIERS FOR FUEL CONSUMPTION ON ROUGH PAVED ROADS

	ROUGHNESS = 1800 mm/km			ROUGHNESS = 5000 mm/km		
SPEED (km/hr)	Pass Car	Light Truck	Bus & Medium Truck	Pass Car	Light Truck	Bus & Medium Truck
16	1.0	1.0	1.0	1.01	1.00	1.03
32	1.0	1.0	1.0	1.05	1.00	1.06
48	1.0	1.0	1.0	1.20	1.01	1.07
64	1.0	1.0	1.0	1.34	1.06	1.08
80	1.0	1.0	1.0	1.50	1.16	1.20

NOTES:

(1) If velocity is less than 16 km/hr, roughness is less than 1800, or vehicle is a heavy truck the multiplier returned is unity.

(2) Speeds over 80 are treated as 80, and roughness over 5000 is treated as 5000.

(3) Interpolate between ranges as necessary.

TABLE 4-7

OIL CONSUMPTION RATES (litres per 1000 km)

	PAVED ROADS	UNPAVED ROADS
PASSENGER CAR	1.2	2.4
LIGHT TRUCKS	1.8	3.6
BUSES, MEDIUM HEAVY TRUCK	4.0	8.0

$$TIREWEAR = (-83.0 + 0.058 * ROUGHNESS) * .001$$

where TIREWEAR is the total wear of all tires per 1000 km, expressed as the consumption of one tire per 1000 km; and with a lower limit, if roughness is below 2000 mm/km, of

$$TIREWEAR = .03$$

For buses and medium and heavy goods vehicles, TRRL found that

$$TIRE = (83.0 + (0.0112 * ROUGHNESS)) * GVW * 10^{-4}$$

with a lower limit, if roughness falls below 1500, of:

$$TIRE = GVW * 10^{-2}$$

where GVW = the gross vehicle weight.

Tire consumption, expressed as the loss of one tire over the 1000 km, is multiplied by the financial and economic costs of the tire as defined before; dividing by 1000 yields the per kilometer financial and economic costs.

Maintenance Parts: The TRRL survey of operators showed maintenance spare parts consumption to be a function of road roughness and the vehicle age in kilometers. This consumption rate is expressed as a percentage of the new financial cost of the vehicle per 1000 km.

As discussed, the HCM does not provide any vehicle age distribution. Therefore, in lieu of the vehicle age in kilometers as required in the equations, the HCM uses the vehicles half-life in kilometers. This half-life is the average annual distance traveled times half the normal life span.

A lower bound is set for road roughness in this set of calculations of 2400 mm/km; upper bounds are specific to the equations. The three equations are shown, with their roughness upper limits, in TABLE 4-8A. One interesting thing to note is that while parts consumption normally varies with the vehicle distance traveled, in the case of buses, TRRL found it to be a function of the square root of the distance traveled.

To compute the economic cost, the financial cost of the parts (not of the vehicle) is multiplied by the economic to financial cost ratio for spare parts. The reason for the difference in methodology is that in many countries, the vehicle is dutied at a different rate than the one used for spare parts. If this is not the case, the ratio is the economic vehicle cost divided by the financial vehicle cost.

Maintenance Labor: The general functional form specified by TRRL for predicting hours of maintenance labor required per 1000 km of vehicle operation is:

$$\text{LABOR HOURS} = f(\text{PCF}, \text{ROUGHNESS})$$

where PCF is the parts consumption factor as computed above.

TABLE 4-8. EQUATION COEFFICIENTS FOR VEHICLE MAINTENANCE

4.8A. PARTS CONSUMPTION FACTOR

	Constant	α_1 Roughness	Vehicle Distance Exponent α_2	α_3 (Scale)	Maximum Roughness
Passenger Cars & Light Trucks	-2.03	+0.0018	1.0	10^{-8}	6500
Buses	-0.67	+0.0006	0.5	10^{-6}	4500
Medium & Heavy Trucks	+0.48	+0.00037	1.0	10^{-8}	7500

General Form of Equation

$$\text{PARTS CONSUMPTION FACTOR} = (\text{CONSTANT} + \alpha_1 \text{ ROUGHNESS}) * \text{DIST}^{\alpha_2} * \text{SCALE}$$

4-8B. LABOUR CONSUMPTION

	Constant	α_1 Roughness
Passenger Cars & Light Trucks	851.0	0.078
Buses	2640.0	0.078
Medium & Heavy Trucks	2975.0	0.078

General Form of Equation

$$\text{LABOUR} = \text{PARTS CONSUMPTION FACTOR} * (\text{CONSTANT} - \alpha_1 \text{ ROUGHNESS})$$

The limits on this equation are 2400 - 6000 mm/km. Whenever roughnesses are encountered which are outside this range, labor hours are set to the nearest limit. The equations for labor hours are shown in TABLE 4-8B.

Costs are computed by dividing hours consumed by 1000 and multiplying by the hourly labor rates to get financial and economic costs per vehicle kilometer.

4.3.4 Annual Fixed Costs

The annual fixed costs of vehicle operation include depreciation, finance, driver and helper wages, administrative overhead, insurance, and licensing and registration. The total costs of these items are assumed as fixed within reasonable ranges around the average annual kilometerage driven, but their allocation on a per kilometer basis will vary with the number of miles that the vehicle will actually be operated during the year. This distance which generally increases when a road is improved, is computed differently for commercial vehicles and private autos, as follows:

Commerical vehicles: For trucks and buses, the assumption is made that the total number of hours per year that the vehicle will be operated remains constant, and that road improvements resulting in speeds above the year round average will increase the average annual kilometerage and reduce the effective fixed charge per kilometer. For purposes of computing these charges, annnual kilometerage is estimated as follows:

$$DIST = AVDIST + UTIL(SPEED - \frac{AVDIST}{UTIL})$$

where DIST = distance driven for purposes of allocating fixed charges (km)

AVDIST = average distance driven per year (km)
UTIL = average hours of vehicle utilization per year
SPEED = speed on the road being evaluated

Autos: For autos, the assumption is made tthat the total number of kilometers driven per year is constant; that is, that road improvements do not result in increases in annual kilometerage. Therefore

DIST = ADVIST

The specific components of fixed annual costs are as follows:

Depreciation: Two separate methods are used to compute the depreciation of the vehicle. The financial depreciation methodology is based upon the observation by TRRL, in their survey in Kenya, that for the most part, the resale value of a vehicle at any time appears to be a funciton of its age in years and not its age in kilometers traveled. This is a marked departure from earlier approaches.(1) One possible explanation for TRRL's observation is that any variations in kilometer age from the year age average are reflected in maintenance. The total depreciation charges allocated to each year equal the new financial cost of the vehicle divided by its age in years.

The economic cost is calculated as a periodic payment to a sinking fund. Using the social rate of interest (SRI) defined earlier, a stream of equal annual payments is calculated whose present value after N years (where N is the vehicle life) is equal to the economic cost of the new vehicle. This annual payment is the annual economic depreciation cost.

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(1) See for example Jan de Wielle Quantification of Road User Savings World Bank Occasional Staff Papers Number Two, John Hopkins University Press, Baltimore, 1966.

The formula for this is:

$$\text{Annual Depreciation, Economic} = \frac{\text{Economic Cost}}{\frac{1}{1 + SRI}} \left(\frac{1 - \frac{1}{1 + SRI}}{1 - \left(\frac{1}{1 - SRI}\right)^N}\right)$$

Financing: In purchasing a car or truck the owner either borrows money or must lose the interest on the money that could have been saved or used elsewhere. This cost of money is a financial operating cost but not an economic one since the loss to the economy has already been accounted for under economic depreciation. The annual cost of financing is the market money rate times one-half of the financial cost of the vehicle. The one-half represents, once again, the assumption that all vehicles have on the average aged halfway.

Wages: The Highway Cost Model treates wages as a fixed expense. The monthly wage bill for drivers and helpers is multiplied by 12 to get the annual cost. Wages have both financial and economic components.

Overhead: The total annual administrative costs of operating a transport company are allocated to each of the company's vehicles to arrive at the annual overhead per vehicle. These costs may have both financial and economic components.

Insurance: The annual cost of insuring the vehicle is a direct financial cost to the owner. Whether there is an economic cost included will depend on whether one is using insurance as a proxy for the cost of accidents or calculating the cost of accidents separately. The HCM assumes the former and annual economic insurance costs are the financial cost less profit and transfer payments.

Licensing and Registration: These charges are both fixed annual financial costs to the operator. They are, however, transfer payments and as such have no economic cost.

Each of the above annual costs (in both financial and economic terms) are divided by the distance traveled during the year to arrive at per kilometer costs.

4.3.5 Time Value of Cargo

Travel time for the link is multiplied by the value of time speed ($/hour) to arrive at cargo holding costs. As discussed earlier, this hourly rate will be different depending upon the type of cargo being carried--higher for perishable cargo and goods that will be placed in service or otherwise used as soon as they arrive, and lower for other goods.

4.4 Traffic Estimates

The Highway Cost Model uses the following procedures to estimate yearly traffic. The previous year's traffic is first increased by a percentage or incremental amount, assuming that operating costs on the link are the same as in the previous year. This calculation amounts to the growth of the existing traffic. After determining the condition of the road, the actual operating costs are estimated and used to adjust the preliminary estimate of traffic in view of any changes in costs which may have arisen, and the demand schedule for transportation. This calculation is as follows

$$VOLUME_F = VOLUME_P * (1 + ELAST(\frac{COST_N - COST_{N-1}}{COST_N})$$

where $VOLUME_F$ = Final estimate of this year's traffic
$VOLUME_P$ = Preliminary estimate of this year's traffic
ELAST = Demand elasticity
$COST_N$ = Operating costs for the link this year
$COST_{N-1}$ = Operating costs on the link last year

V. THE YALA-BUSIA CASE STUDY (ABRIDGED)

5.1 Introduction

This chapter presents an application of the Highway Cost Model (HCM) to the Yala-Busia Road in Kenya. This example is intended to demonstrate the HCM's abilities in estimating the costs to construct, maintain and utilize a new highway facility. This is a limited application and, as such, does not call upon such capabilities as staged construction, reconstruction, or capital-labor tradeoffs.

The experiment investigates the total costs of building a new road link where none presently exists. Two level of construction investment--a gravel and a paved (DBST) surface--are posited. Each road is examined using a light and an intensive maintenance policy specification over an analysis period of twenty years from 1977, the opening year of the road. Each construction/maintenance option, e.g. gravel road/high maintenance policy, will be subjected to two traffic volumes. The low volume traffic will start at 200 ADT and the high volume will begin with 400 ADT. The rates of growth of the traffic are identical.

The input information used for this Yala-Busia Road example, covering construction costs and standards, terrain, environment, vehicle fleet descriptions, and traffic volumes and mix was supplied by the Transport Projects Research Division of the World Bank (IBRD). Where data was not supplied through this source (primarily maintenance costs and policies, and shadow prices), the source or assumption is noted.

5.2 Input Data Documentation

5.2.1 Alignment and Environment

The Yala-Busia Road is only 15.1 kilometers passing through a region of

essentially uniform environmental and terrain conditions. This uniformity allows the road to be analyzed as one segment. This data is summarized in TABLE 5-1.

TABLE 5-1

EXISTING ALIGNMENT AND ENVIRONMENTAL DATA
YALA-BUSIA ROAD

Road Length		15.1 kilometers
Ground Cover		100% medium vegetation
Surface Moisture:	dry season	0.0%
	wet season	6.0%
Average Annual Rainfall		1750 millimeters
Season Length:	dry	8 months
	wet	4 months
Subgrade CBR		9%
Drainage Factor		1.0
Total Number of 10 Meter Contour Lines Crossed		19
Altitude		1413 meters A.S.L.

The TRW earthwork model, used for this case study, requries the density of contour lines over the segment length[1]. In the absence of a relief or contour map, the original ground station elevations, provided in the IBRD data, were converted to 10 meter contours over the road length. From this, the density of contour lines, was calculated. The new road alignment will be built to the vertical and horizontal standards shown in TABLE 5-2 .

[1] For details, refer to Chapter II (Construction Submodel)

TABLE 5-2

FINAL HIGHWAY ALIGNMENT

Average Horizontal Curvature	18.21 degrees/km
Average Rise	5.0 meters/km
Average Fall	9.0 meters/km
Maximum Grade	3.0%

5.2.2 Construction Design Standards

Cross-Section: Two road construction solutions will be examined, one gravel surfaced and the second paved with a double bituminous surface treatment (DBST). Both solutions will have the same standard cross-section shown in Figure 5-1. The total width cleared is 20 meters.

Pavement: The gravel surfaced road will have a single layer pavement of 15 cm of gravel having a structural coefficient of 0.10. The shoulders will be of the same material and thickness . Construction will take two years.

The DBST road will have a three layer, 32.50 cm pavement. The sub-base will be 17.50 cm of gravel; the base,13.0 cm of cement stabilized material with a structural coefficient of 0.25; and a 2.0 cm DBST surfacing with a structural number of 0.30. The shoulders will be 30.50 centimeters of gravel. On opening, the DBST road will exhibit a PSI of 4.10. Construction will take 2 years.

Unit Costs: The unit costs for construction are given in TABLE 5-3.

TABLE 5-3

CONSTRUCTION UNIT COSTS

Sub-base Description	Units	Labor Skilled	Labor Unskilled	Equip	Material	Overhead	Total
Clearing Med	HA	540.00	65.00	760.00	0.00	160.00	1535.00
Unclassified Ex	M3	0.75	0.25	20.63	0.00	1.00	8.00
Bit DST	M3	60.00	20.00	120.00	160.00	40.00	400.00
CT base	M3	20.63	6.87	41.00	55.00	13.75	137.50
Gravel	M3	7.50	2.50	15.00	20.00	5.00	50.00
24" R.C. Pipe	M	19.42	58.25	51.78	103.56	25.89	258.90
30" R.C. Pipe	M	30.00	86.00	80.00	160.00	40.00	396.00
36" R.C. Pipe	M	42.38	121.49	113.02	226.04	56.51	559.44
42" R.C. Pipe	M	55.13	158.03	147.00	294.00	73.40	727.66
48" R.C. Pipe	M	71.18	204.06	189.82	379.64	94.91	939.61

Only total unit costs were available from the data, and judgement and experience were applied for the breakdown into subcomponents. In addition, the earthworks costs were not provided in a form consistent with normal HCM input specifications. The 8 shillings/cubic meter price for unclassified excavation is a composite of the more detailed prices provided.

There are no minor or major river crossings on the Yala-Busia Road to be accounted for.

Miscellaneous costs of Kshs 936,200, were supplied.

General construction overhead and supervision is 5% of the construction cost.

5.2.3 Maintenance Operations

Policies: Each road will be maintained to a light and an intensive upkeep schedule. The light and intensive policy specifications for both roads are described in TABLE 5-4.

TABLE 5-4

MAINTENANCE POLICIES

Item	Light Policy	Intensive Policy
1. Gravel Surface blading		
dry season	1 per month	4 per month
wet season	1 per month	2 per month
2. Gravel resurfacing--restore to 15 cm when gravel thickness is:	0.0 cm	5 cm or every 4 years (1)
3. Seal and patch existing cracks in DBST, to a:	20% maximum	50% maximum
4. Seal coat road	never	every 5 years or when surface is 25% cracked
5. Apply 2 cm DBST overlay	PSI = 1.0	PSI = 2.0 (2)
6. Shoulder grading	none	twice a year
7. Brush control & culvert cleaning	once a year	twice a year

(1) after year 19, regravel only if 0.0 thickness
(2) no overlaying will occur after year 19

Unit Costs: The unit costs for the maintenance operations specified above are given in TABLE 5-5. These costs were not supplied by IBRD, and

TABLE 5-5

MAINTENANCE UNIT COSTS

Description	Units	Labor Skilled	Labor Unskilled	Equip	Material	Total
G-surfc grade(D)	KM	5.42	0.00	98.00	0.00	103.42
G-surfc grade(W)	KM	5.42	0.00	140.80	0.00	146.22
Gravel resurface	M3	0.02	0.05	0.17	40.00	40.24
B-surfc patching	M2	0.51	0.65	1.21	3.60	5.97
B-routine sealing	M2	0.02	2.83	36.06	16.56	55.47
Bit-seal coating	M2	0.08	0.05	0.05	1.62	1.80
Bit-overlay	M3	6.00	34.00	40.00	120.00	200.00
Shoulder grading	KM	5.42	0.00	98.00	0.00	103.42
Brush Control	HA	0.00	480.00	136.00	0.00	616.00
Culvert Cleaning	M3	0.00	0.25	0.50	0.00	0.75

total costs were either taken from the construction unit costs in TABLE 5-3 or from costs of similar operations in other reports. Judgement and experience were used to break the total costs into the subcomponents of labor, equipment and materials.

There is a 15% overhead and supervision cost on all maintenance activity costs.

5.2.4 Vehicle Fleet

Vehicle Characteristics: Seven representative vehicle types were identified for the Yala-Busia Road. These are summarized in Table 5-6. Such items as economic prices and annual fixed costs of operation were not provided by the IBRD. Eighty percent of the financial price was used for the economic price. The annual fixed cost of operation was estimated as a function of the new price of the vehicle, one percent for passenger cars and two and one-half percent for the others.

TABLE 5-6

VEHICLE DESCRIPTIONS

Names	Passenger Car	Light Comm	Bus	Heavy CMMA	Heavy CMMB	Heavy COMC	Heavy CMOE
Category	1	2	3	4	5	5	5
Fuel type	G	G	D	D	D	D	D
Horse Power	80.00	100.00	100.00	104.00	150.00	177.00	177.00
Speed	80.00	72.00	72.00	72.00	64.00	64.00	64.00
Tare	0.50	2.40	3.00	4.10	9.20	11.70	13.40
Maximum Load	0.50	2.00	3.00	3.40	10.80	20.00	21.60
Axle Type	1 - .50	1 - .50	1 - .50	1 - .50	1 - .25	1 - .22	1 - .13
/Weight	1 - .50	1 - .50	1 - .50	1 - .50	2 - .75	1 - .44	2 - .37
						1 - .17	1 - .25
						1 - .17	1 - .25
Financial							
Vehicle	33,000.00	40,000.00	163,000.00	220,000.00	165,000.00	220,000.00	278,000.00
Tire	180.00	256.00	1,384.00	878.00	1,384.00	1,384.00	1,915.00
Standing Costs	330.00	1,000.00	4,075.00	5,500.00	4,124.00	5,500.00	6,950.00
MNT Labor	17.50	17.50	17.50	17.50	17.50	17.50	17.50
Driver	0.00	750.00	2,250.00	2,910.00	1,960.00	2,550.00	2,550.00
Per litre	G = 1.56	D = 1.16	Oil = 3.25				
Financial Discount Rate	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Economic							
Vehicle	26,400.00	32,000.00	130,400.00	176,000.00	132,000.00	176,000.00	222,400.00
Tire	144.00	205.00	1,107.00	702.00	1,107.00	1,107.00	1,532.00
MNT Labor	17.50	17.50	17.50	17.50	17.50	17.50	17.50
Driver	0.00	750.00	2,250.00	2,910.00	1,960.00	2,550.00	2,550.00
Per litre	G = 0.842	D = 0.58	Oil = 3.02				
Social Discount Rate	0.12	12.00	12.00	12.00	12.00	12.00	12.00
Parts Ratio	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Utilization							
hours/year	375.00	1,800.00	1,800.00	2,700.00	1,800.00	1,800.00	1,800.00
km/yr	16,250.00	40,450.00	81,450.00	70,300.00	70,300.00	70,300.00	93,750.00
years	10.00	8.00	6.00	8.00	8.00	8.00	8.00

Base Volumes and Mix: Two base traffic volumes have been considered, 200 ADT and 400 ADT. The mix by vehicle type is shown in TABLE 5-7.

TABLE 5-7

BASE TRAFFIC MIX

Base ADT Total	Passenger Cars	Light Commercial	Bus	Heavy A	Heavy B	Heavy C	Heavy D
200	60	54	46	32	2	2	4
400	120	108	92	64	4	4	8

Growth Rates and Elasticity: The volumes given above are for 1977, the opening year of the road. From 1977 to 1997, traffic will grow at the annual percentage rates given in TABLE 5-8.

TABLE 5-8

ANNUAL GROWTH RATES (%)

Passenger Cars	Light Commercial	Bus	Heavy A	Heavy B	Heavy C	Heavy D
7.0	7.0	3.0	7.0	10.0	10.0	7.5

The elasticity of demand for price changes is specified as zero. This means that annual fluctuations in financial operating costs will have no effect on the growth rates specified in TABLE 5-8.

5.3 Analysis of Results

5.3.1 Construction Costs

The undiscounted financial economic costs of construction are itemized in TABLE 5-9 for the (a) gravel and the (b) DBST road solutions. As noted earlier, the breakdown into labor, materials, equipment etc., are based on the percentages used in other reports applied to the total financial costs per unit supplied by the IBRD. In addition, the percentage local currency as well as the economic prices were not supplied.

TABLE 5-10 compares the HCM estimated totals with those supplied by the IBRD. Costs estimates for site clearing and pavement plus shoulders show no significant difference This is not surprising since these calculations are straightforward area or volume, times price calculation. Earthwork (unclassified) was 18.5% higher on the gravel road and 11.1% on the DBST using the HCM estimate. Because numbers for earthwork were not specified in an HCM compatible format, it is difficult to explain these differences. In addition, since the IBRD data gives only a total cost, it is not possible to compare quantities. In any case, if we call the IBRD estimate "exact", then for both roads, the HCM estimate is within the range of acceptable feasibility level estimates.

The major differences occur in estimates of drainage where HCM estimates exceed IBRD estimates by over 100%. The HCM drainage estimate was made using a statistical distribution scheme based on terrain, rainfall, peak intensity, and embankment height to predict drainage requirements. The IBRD supplied estimate was computed using a fixed culvert size (0.61 meters) and a fixed spacing (444.0 meters) for the road. A 0.61 meter diameter pipe was the smallest recommendation by the HCM and although 65% of the pipe footage was of this size, larger sizes were also required.

TABLE 5-9

UNDISCOUNTED CONSTRUCTION COSTS YALA-BUSIA ROAD

DESCRIPTION	QUANTITY	UNIT	SKILLED LABOR	UNSKILLED LABOR	EQUIPMENT	MATERIAL	OVERHEAD	TOTAL FINANCIAL	LOCAL CURRENCY	TOTAL ECONOMIC
(a) Gravel Road										
CLEARING MED	30.	HEC	16610.	1963.	22952.	0.	4832.	46357.	18978.	54784.
UNCLASSIFIED EX	300908.	CM	225681.	75227.	1805447.	0.	300908.	2407261.	1426302.	2949273.
GRAVEL	22650.	CM	169875.	56625.	339750.	453000.	113250.	1132498.	565117.	1212056.
24" R. C. PIPE	706.	LM	13706.	41110.	36543.	73087.	18272.	182717.	79299.	178538.
30" R. C. PIPE	282.	LM	8469.	24278.	22584.	45168.	11292.	111790.	49007.	109540.
36" R. C. PIPE	76.	LM	3221.	9234.	8590.	17180.	4295.	42519.	18640.	41664.
42" R. C. PIPE	11.	LM	599.	1716.	1596.	3192.	798.	7901.	3463.	7742.
48" R. C. PIPE	11.	LM	773.	2216.	2061.	4122.	1030.	10202.	4472.	9997.
TOTAL FINANCIAL COSTS			438933.	212367.	2239522.	595748.	454677.	3941244.	2165278.	
TOTAL ECONOMIC COSTS			500383.	149719.	2933774.	565960.	413756.			4563590.
(b) DBST Road										
CLEARING MED	30.	HEC	16610.	1963.	22952.	0.	4832.	46357.	18978.	54784.
UNCLASSIFIED EX	300908.	CM	225681.	75227.	1805447.	0.	300908.	2407261.	1426302.	2949273.
BIT CST	1812.	CM	108720.	36240.	217440.	289920.	72480.	724799.	361675.	775716.
CT BASE	11778.	CM	242980.	80915.	485842.	647790.	161947.	1619473.	808118.	1733268.
GRAVEL	34277.	CM	257077.	85692.	514155.	685539.	171385.	1713847.	855210.	1834246.
24" R. C. PIPE	706.	LM	13706.	41110.	36543.	73087.	18272.	182717.	79299.	178538.
30" R. C. PIPE	282.	LM	8469.	24278.	22584.	45168.	11292.	111790.	49007.	109540.
36" R. C. PIPE	76.	LM	3221.	9234.	8590.	17180.	4295.	42519.	18640.	41664.
42" R. C. PIPE	11.	LM	599.	1716.	1596.	3192.	798.	7901.	3463.	7742.
48" R. C. PIPE	11.	LM	773.	2216.	2061.	4122.	1030.	10202.	4472.	9997.
TOTAL FINANCIAL COSTS			877835.	358589.	3117208.	1765596.	747239.	6866867.	3625162.	
TOTAL ECONOMIC COSTS			1000732.	252805.	4083543.	1677696.	679988.			7694763.

TABLE 5-10

Comparison of Undiscounted Construction Costs

(000's shillings)

Item	Gravel Road			DBST Road		
	IBRD Estimate	HCM Estimate	Difference (%)	IBRD Estimate	HCM Estimate	Difference (%)
1. Site Clearing	46.4	46.4	- nil -	46.4	46.4	- nil -
2. Unclassified Earthwork & Retaining Walls	2,031.8	2,407.3	+ 18.5	2,166.0	2,407.3	+ 11.1
3. Drainage	164.6	355.1	+115.7	164.7	355.1	+111.6
4. DBST	—	—	—		724.8	
6. Cement Treated Base	—	—	—	3,137.0	1,619.5	- nil -
7. Gravel	679.5	1,132.5	- nil -	921.0	1,713.8	
8. Gravel Shoulders	453.0					
9. Miscellandous	936.2	936.2	*	936.2	936.2	*
Sub Total	4,312.4	4,877.5	+ 13.1	6,435.1	7,803.1	+ 21.3
5% Overhead and Supervision	215.6	243.9		321.8	390.2	
TOTAL	4,527.0	5,121,4	+ 13.1	6,756.9	8,143.3	+ 21.3

* Number supplied by IBRD as a line item

It is probable that the "correct" estimate lies somewhere between the HCM's statistical averages and the IBRD's rule-of-thumb approximations[1].

Discounted Economic Costs: To compare the total cost of each solution it is necessary to discount the time stream of construction costs. From TABLE 5-9 we find the total economic cost, for gravel, 4563590 shs and for DBST, 7694763. To these we add the 936,200 shs of miscellaneous costs (the economic cost is the same as the financial) and 5% for overhead and supervision. Costs are incurred two thirds the first year; one-third, the second. Using a discount rate of 12% per year, yields a discounted economic cost of construction in 1975 of 4968200 shillings for the gravel road, and 7,796,800 shillings for the DBST road.

5.3.2 Maintenance and Deterioration

The economic costs for maintaining the two road solutions with two levels of traffic using two intensities of maintenance, discounted to 1975 at 12%, are given in TABLE 5-11. The 15% for overhead and supervision has been included.

TABLE 5-11

DISCOUNTED MAINTENANCE COSTS*

(000's shillings)

	200 ADT		200 ADT	
	Light	Intensive	Light	Intensive
Gravel	864	1351	1238	1718
DBST	438	1145	803	1943

[1] For a discussion of an alternate estimation scheme using the locations of drainage read from topo maps, see Chapter Two.

* includes 15% for overhead and supervision

Costs are higher on the gravel road than the DBST road in all cases except the 400 ADT intensive maintenance. The latter was due to more extensive crack patching and crack sealing resulting from the heavier traffic loading. Figure 5-2 shows the deterioration of the surface over time for the gravel road under both maintenance policies and both traffic loadings. The intensive policy called for regravelling at the end of the project analysis period. However this regravelling is considered salvageable and the costs (85,000 shs) have been deducted from the total maintenance costs shown in TABLE 5-11. For consistency the costs of the light maintenance have been adjusted for the salvageable gravel in proportion to the gravel remaining at the end of 1995; 56% for the 400 ADT and 21% for the 200 ADT.

Two additional regravellings were required by the 400 ADT for both the light (5 versus 3) and the intensive (6 versus 4) policies.

The PSI of the DBST road over time for all four cases is shown in FIGURE 5-3. No overlay is required for 200 ADT with light maintenance since its PSI is only 1.1 at the end of the analysis period. The 400 ADT a slightly more rapid deterioration but only enough to warrant a 1996 overlay. The discounted cost of this overlay (37,000 shs) has been salvaged from (credit to) the maintenance cost.

The intensive policy is sufficient to allow no increase in deterioration between the 200 ADT and 400 ADT traffic. The overall rate of deterioration, however, is only marginally slowed over the light maintenance and had the intensive overlay been delayed from a PSI of two to one the final PSI in 1996 would have been about 1.5. This indicates that the overlay was not warranted given the other operations carried out under the intensive schedule, if we allow the minimum serviceability of the road to drop to the levels permitted with a light maintenance schedule. This has been adjusted by deducting an 87% salvage value for the intensive 200 ADT solu-

FIGURE S-2 GRAVEL THICKNESS VERSUS TIME

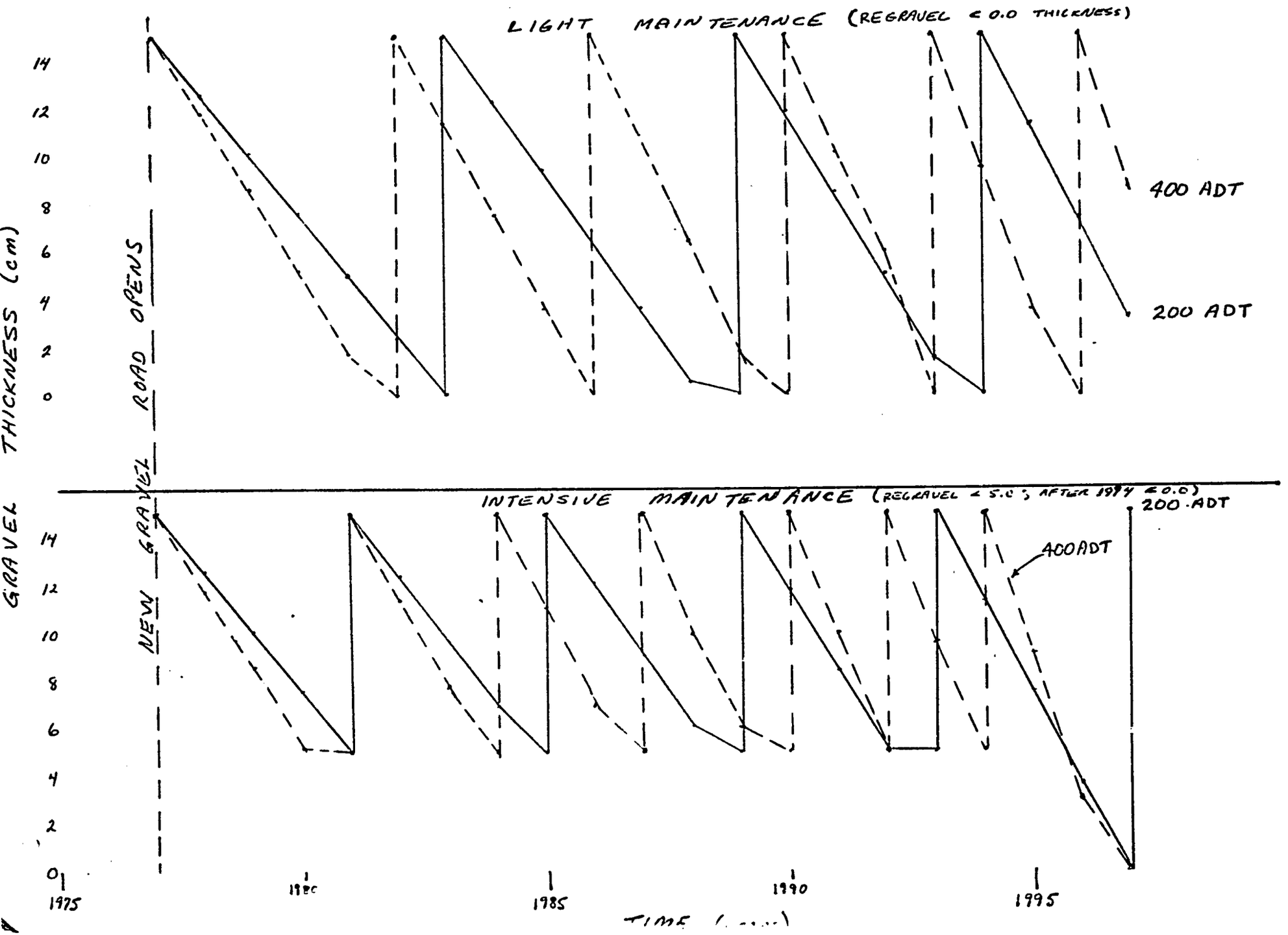
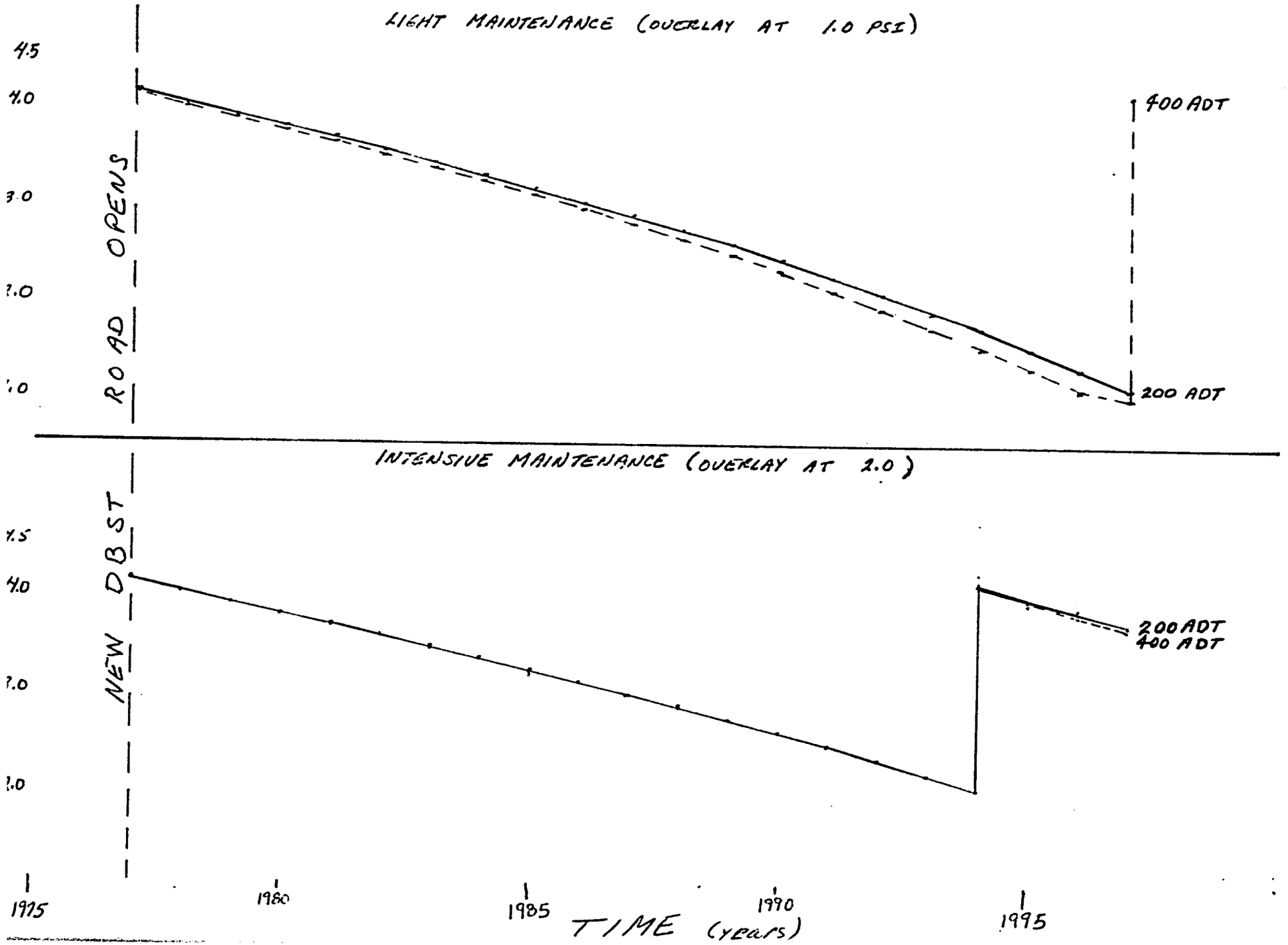


FIGURE 5-3 PSI VERSUS TIME - DBST ROAD



tion and 85% for the 400 ADT solution.

Maintenance costs given in TABLE 5-11 have been adjusted to reflect any salvage left at the end of the analysis.

Maintenance expenditure decisions are reflected in pavement surface conditions which directly impact the user's cost of operation. Lower expenditures usually result in higher user costs; the extent of this shift is an important decision variable.

5.3.3 Vehicle Operating Costs

The economic cost stream of vehicle operations, discounted to 1975 at 12%, is given in TABLE 5-12 for all eight solutions.

TABLE 5-12

DISCOUNTED VEHICLE OPERATION COSTS

(000's shillings)

	200 ADT		400 ADT	
	Light	Intensive	Light	Intensive
Gravel Road	9778	9518	20282	19305
DBST Road	8305	8261	16901	16747

As expected, in all cases shown, vehicle operating costs decrease as road type improves from gravel to DBST, and as maintenance expenditure increases. Two problems for the decision maker*, are (1) the tradeoff between the savings to the users and the incremental expenditure for government, and

*If the road was being funded externally, not the case here, the tradeoff between construction costs (funded) and maintenance costs (not funded) would also need to be considered.

(2) which combination consumes the least of the country's scarce resources. These scarce resources could be skilled labor, foreign exchange, or simply total cost. We shall consider total cost.

The total economic costs for each road solution discounted at 12% to 1975 are presented in FIGURE 5-4.

Considering the problem for 200 ADT the decision is quite simple. The gravel road, lightly maintained not only costs the economy the least by 0.2 to 1.6 million shillings, but also requires the least government expenditure by 0.5 to 3.1 million shillings.

Operators would only save about 1.5 million if the government built the DBST road and applied intensive maintenance--at an incremental cost of 3.1 million shillings.

The decision for the 400 ADT case is not so clear cut. In terms of the total economic resource consumption, the DBST road, lightly maintained would be the best choice among these four solutions. However, if government expenditures for highway are constrained,* then the two gravel road solutions must be examined more closely.

If the gravel road were built and lightly maintained, the economy would lose one million shillings however, government expenditure would decrease by 2.4 million with the user's bearing the burden of a 3.4 million shillings increase. The savings to government are clearly substantial however the extra cost to the economy is too.

A more nearly optimal solution is provided by increasing to intensive maintenance. Here the loss to the economy is only 0.5 million and the savings to government 1.9 million over the DBST/light solution. However, compared to the gravel/light solution, the gravel/intensive solution

*or if there is a ceiling on the international funding for construction of this road

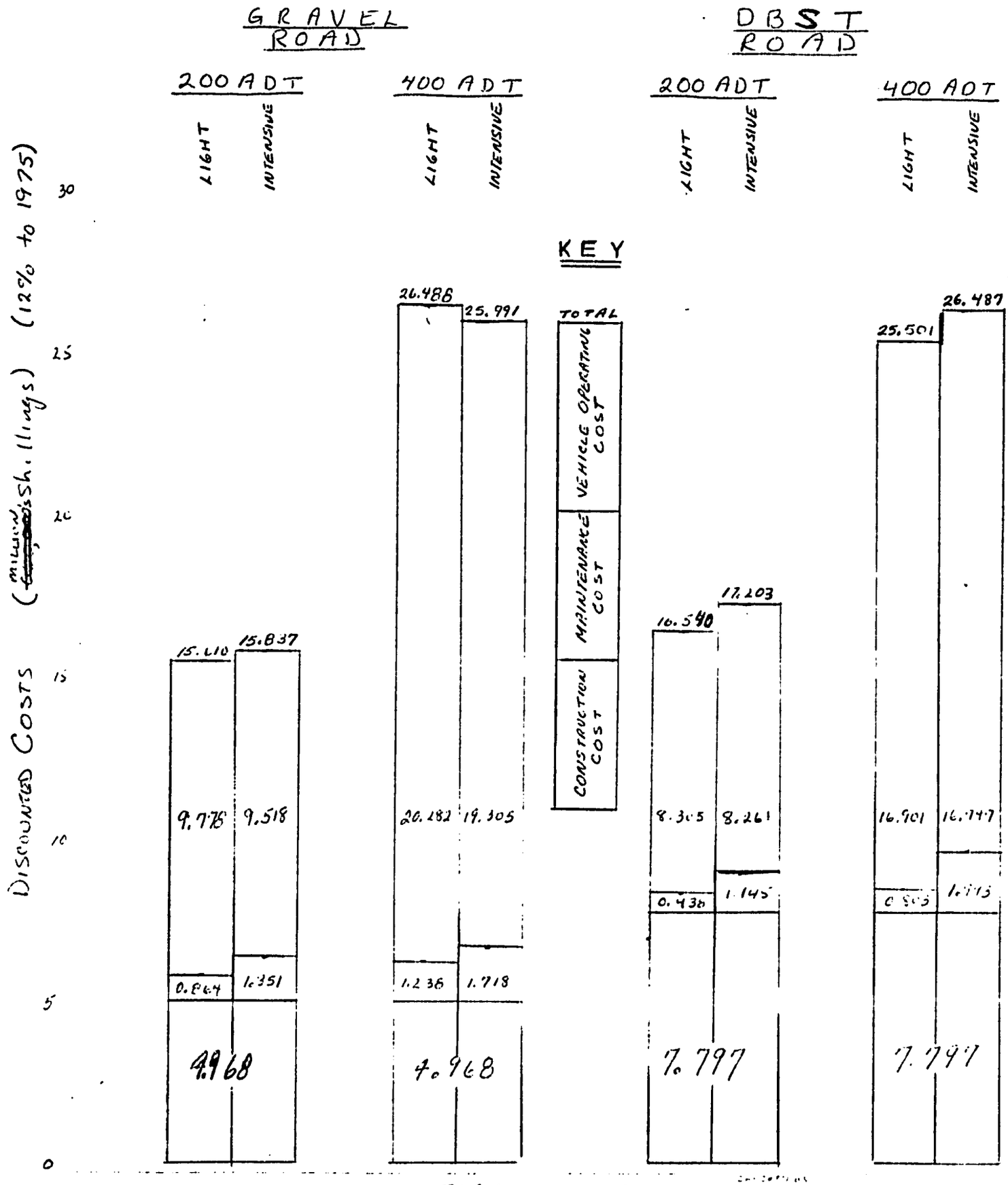


FIGURE 5-4

COMPARISON OF DISCOUNTED TOTAL COSTS FOR ALL SOLUTIONS

saves the economy 0.5 million at a cost of 0.5 million to government. This solution also saves the user 1.0 million over the gravel/light solution. Extrapolating this trend (a shaky but testable hypothesis), one suspects that an additional increment of 0.5 million in government expenditure would reduce the total cost to the economy to the same level as the DBST/light solution, yet still saving government 1.4 million shillings over the DBST/light solution. This discussion is summarized in TABLE 5-12.

TABLE 5-12

400 ADT ROAD SOLUTIONS - COMPARISON OF COSTS

(million shillings discounted at 12% to 1975)

	DBST/LIGHT	GRAVEL/LIGHT	GRAVEL/INTENSIVE	INCREASED GRAVEL/INTENSIVE
Government Costs	8.6	6.2	6.7	7.2
Total Cost	25.5	26.5	26.0	25.5
Government Saving		2.4	1.9	1.4
Loss to Economy		1.0	0.5	0.0

5.3.4 Conclusion

By review of the multi-solution output generated by the HCM, a decision maker, engineer, or analyst can examine more potential trade-offs and can come closer to finding the optimum investment solution given the decision variables and constraints defining the problem. In addition, professional resources can be saved the expense of examining variations on solutions when no tradeoffs exist.