AN APPROACH FOR INTEGRATING HIGHWAY MAINTENANCE INTO THE DESIGN PROCESS

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ABSTRACT

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Submitted to the Department of Civil Engineering on August 24, 1970 in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

In spite of the importance of maintenance in providing highway transportation, little consideration is usually given to maintenance costs and effects during the overall planning and design of highways.

This study addresses the problem of integrating maintenance into the highway design process. To consider maintenance as an integral part of the overall design problem requires prediction of the costs and effects of maintenance for proposed designs. The deterministic model developed during this study predicts these costs and effects for low volume roads as a function of design characteristics, load, environment, and the proposed maintenance policy. The model is programmed for computer use and the maintenance costs and roadway conditions can be quickly and cheaply estimated.

The model is used, in conjunction with predictions of construction and road user costs, to estimate the total cost required to provide highway transportation. This allows comparison of strategies on the basis of total cost of transportation. Examples are given to illustrate use of the model for making these comparisons.

The relatively quick estimation of future costs for competing strategies also allows the application of other decision making techniques. The concepts of decision theory and maintainability are explored as means of incorporating uncertainty and future constraints on maintenance into the decision process.
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1.1 DISCUSSION OF MAINTENANCE

Highway maintenance is becoming recognized as one of the important aspects of providing highway transportation. Not only does maintenance require a substantial share of the highway budget in most areas, but it also has important effects on the operation and service life of the system. This study presents an analytical approach for integrating these effects of maintenance into the design process.

1.1.1 Definition

Maintenance can be broadly defined as the work performed on a system, after the initial construction, to defer the progress of deterioration, or to restore the partially deteriorated system to a condition closer to its initial state. This does not include reconstruction work which typically results in a system superior to the original or involves the complete destruction and rebuilding of a substantial part of the system.

A maintenance operation should be done only if it has a positive effect on the performance level or service life of the system, and if these effects are worth the cost of the operation. Performance is used here to include all aspects...
of the system's capability to accomplish its goals.

1.1.2 Fundamental Questions of Maintenance

There are three fundamental questions that must be answered if maintenance is to play its proper role in providing the most useful system for the cost:

A. WHAT IS THE BEST BALANCE BETWEEN INITIAL SYSTEM COST AND FUTURE MAINTENANCE COST,

B. HOW MUCH MAINTENANCE SHOULD BE DONE ON EXISTING SYSTEMS,

C. HOW CAN THE MAINTENANCE OPERATIONS BE DONE MOST EFFICIENTLY?

Almost all recent efforts devoted to the study and improvement of highway maintenance have been directed to the third type of question. However, the first two questions raise issues of, how much and what kind of maintenance should be provided, which are fundamental to the problem of providing the most economical system. These should be addressed along with the more limited questions of providing the most efficient maintenance. This study is directed to these first two questions.

The first question is the familiar question of high initial cost and low maintenance cost or low initial cost and high maintenance cost. This question should be investigated for each level of service proposed during design. Selection of the appropriate level of service should, of course, also
be part of the design process. In essence, construction cost, maintenance cost and service level should all be considered design variables.

The second question asks how well the existing system should be maintained. The original maintenance policy should be adjusted during operation, to take advantage of current system behavior. Ideally, maintenance policy should be adjusted throughout the life of the system.

The third question deals with the planning, management and detailed operations used by the maintenance organization to perform the various maintenance operations. This is basically a question of maintenance management.

The third question can be addressed as if maintenance were an independent problem. However, to deal effectively with the first two questions requires an understanding of the inherent relationships between maintenance and the rest of the system.

These relationships are the basis for the compromises, or tradeoffs, between maintenance costs and other system costs of interest to this study.

1.1.3 Relationship Between Maintenance and the Constructed System

In addition to the direct effect of maintenance cost, maintenance affects the system through both performance, or
service level, and initial cost. Thus, there are two fundamental tradeoffs involving maintenance.

The first tradeoff is between maintenance costs and user benefits. In general, better maintenance increases user benefits. These benefits may be lower user operating costs, higher reliability, greater comfort, better appearance or whatever benefits the system is designed to produce.

The second tradeoff is between maintenance cost and construction, and reconstruction costs. Maintenance and construction costs are related in two ways.

The first and most obvious relationship is the effect that a system's initial characteristics have on future maintenance demand. This is a question of balancing initial cost against maintenance cost for the life of the system.

The second relationship between maintenance and construction costs is the effect of maintenance on how long the system will last before reconstruction is required. For instance, a maintenance policy that results in premature failure will require early reconstruction or replacement. This increases the total construction and reconstruction costs of providing the system. Conversely, a policy that prolongs a system's life will decrease these costs.

These tradeoffs should be considered during design if the best system for the cost is to be achieved. Maintenance during the life of the system should be taken into consideration.
during design. The costs of this future maintenance should be systematically weighed against construction costs and the expected future benefits of the system. The above tradeoffs are the means for weighing these costs and benefits.

All of the above tradeoffs can be considered during design. In addition, the tradeoffs of maintenance cost vs. user benefit, and maintenance cost vs. reconstruction costs can be considered for existing systems. Maintenance policy on existing systems should be adjusted to obtain the most efficient operation considering the balance of maintenance costs, user benefits and construction costs.

Consideration of the tradeoffs discussed in this section is important for the efficient use of highway resources. However, these tradeoffs are usually considered only qualitatively since the information needed for a more rigorous treatment is seldom available.

1.2 OBJECTIVE AND SCOPE

The objective of this thesis is to devise systematic and practical techniques to allow consideration of the first two fundamental questions of highway maintenance. a. What is the best balance between initial system cost and future maintenance cost. b. How much maintenance should be done on existing systems. The answers to these questions involve the interactions of maintenance with other elements of the highway
system. The techniques developed must take these interactions into account. At the same time, the techniques must be simple enough to encourage use by engineers and others responsible for the design, construction, and operation of highway systems.

Highway transportation was chosen for this study as a field where maintenance is recognized as an important problem. The area of interest was limited to low volume, two land roads so that realistic workable techniques could be developed. This reduced the complexity of economic analysis since many complications, such as congestion, accident losses, and traffic delays as a result of maintenance operations, can be ignored for low volume roads. Another factor that made low volume roads an attractive choice for this study was the importance of maintenance costs in relation to construction and user costs.

Although limiting consideration to low volume roads somewhat limits the applicability of the study, these roads constitute an important area of highway transportation. They are a common and important class of roads in most countries. For example, of the 3.7 million miles of roadway in the United States in 1968, 2.0 million miles or approximately 57% were unpaved. Another 23% were low volume paved roads (1)*. Approximately 80% of all roads in the U.S. are of the type

* Numbers in parentheses refer to references
dealt with in this study. In developing countries low volume roads are of even greater relative importance and in many cases are the only type in use.

Although this study is limited to one class of roads, the principles used are valid for other types of roads and other types of civil engineering facilities. The study strongly suggests that similar techniques could be developed for these other systems.

1.3 BACKGROUND DISCUSSION OF HIGHWAY MAINTENANCE

1.3.1 Reasons for Problem

Highway maintenance is now being recognized as one of the important problem areas associated with highway transportation. Until recently, highway maintenance problems have been overshadowed by the more visible construction programs. In the United States this has been particularly true as the Interstate Highway program attracted most of the available engineering and administrative attention. A similar situation is present in some of the developing countries where major efforts to improve the transportation system have been concentrated on new construction, sometimes at the expense of maintenance budgets. Recently, however, maintenance is discussed more and more as one of the major problem areas of highway transportation. The factors contributing to maintenance problems are: increasing demand, premature failures,
and the inherent problems of maintenance operations and organizations.

1.3.1.1 Maintenance Demand: Demand for maintenance has been rapidly increasing, in both the United States and many developing countries. Not only has there been an increase in total maintenance requirements but the percentage of the total highway budget spent for maintenance has also increased. In the past, highway departments in the U.S. have allocated as little as 10 to 15 percent of their budgets to maintenance. Current maintenance requirements are claiming 20 to 30 percent of the highway budget. The estimated cost of highway maintenance in the U.S. for 1970 is $5.1 billion out of a total highway budget of $20 billion. Projections by the Bureau of Public Roads indicate that the maintenance share of the total highway budget will rise to almost 50 percent in the period between 1973 and 1985 (2).

The fraction of total highway expenditures spent for maintenance in developing countries is similar to that in the U.S. Statistics from these countries indicate that 25 to 40 percent of the total highway budget is spent on maintenance (3).

There are undoubtedly many reasons for this rapid increase in maintenance expenditures. One of the most obvious is increased traffic. The demand for most maintenance activities
increases with increasing traffic. Since traffic volume has grown rapidly in both the U.S. and developing countries in recent years, maintenance demand has also increased.

Other factors that contribute to the increase of maintenance expenditures in the U.S. are the growing demands of the Interstate system, the difficulties associated with maintaining the urban sections of the highway system, the age of much of the existing system and the higher level of maintenance expected by the public.

Most of the Interstate system now in service is still relatively new. Consequently, most of the maintenance associated with physical deterioration is still in the future. As the rest of the Interstate system is completed and put into service, maintenance demands will claim an increasing share of the highway budget.

Highway maintenance is inherently more difficult in cities. Space limitation and traffic congestion increases the difficulty of most maintenance operations. There are also fewer periods of low traffic volume available for maintenance work that restricts traffic. As more and more of the nation's traffic has concentrated in these urban areas, maintenance costs have increased and will continue to increase.

The higher level of maintenance presently expected by the public may be one of the biggest factors in the maintenance cost increase. Faster and more complete snow and ice
removal, smoother surfaces and cleaner streets all require more maintenance money.

The nationwide resistance to highway construction, especially urban freeway construction, indicates that the public is no longer willing to accept, without objection, the ugliness and noise associated with many highways. This has resulted in increased efforts in landscaping and other design features to make highways less objectional to users and residents. Most of these design features add to the maintenance requirements.

Whatever the reasons, the reality of increased maintenance workload is now widely recognized as one of the most critical problems confronting highway administrators.

1.3.1.2 Inadequate Maintenance: Another factor that has increased awareness of the importance of maintenance, especially in the developing countries, has been the premature failure of roads because of inadequate maintenance. This has been noted in several developing countries where economic aid was available for construction but maintenance was left to the resources of the local government. Where these resources have been inadequate, extreme deterioration has sometimes led to the loss of much of the initial highway investment as well as high costs for the road users (3,4).

A similar situation exists on some systems in the U.S. where pressure for matching funds for federally aided con-
struction has caused needed maintenance operations to be postponed. This has occasionally led to advanced deterioration of parts of the highway structure and premature loss of initial investment.

1.3.1.3 Operational Difficulty: The nature of highway maintenance operations and the organizations that have evolved to handle these operations make improvement of the typical maintenance organization a complicated and difficult problem.

Maintenance is now usually done by small, relatively independent work units operating with a minimum of systematic planning or engineering control. The management and effectiveness of these units is often highly dependent on the common sense and experience of the local supervisor. These supervisors typically receive little support in terms of technical information or management training from the professional sections of their highway departments. As a result, they are often less effective in their jobs than they might be with proper support.

Unfortunately, the nature of highway maintenance adds to these difficulties. Maintenance includes many operations ranging from the very simple to jobs requiring a high degree of skill and judgment. Unpredictability of the weather complicates maintenance planning. Furthermore, maintenance activities usually involve a small number of men working over a relatively large geographical area, resulting in communication
and coordination problems that hamper the efficient use of men, materials and equipment.

Another factor that has impeded progress in the maintenance field is the presence of an entrenched political patronage system in many organizations in the United States (5). There is also evidence that similar problems exist in some of the developing nations (6). The presence of a patronage system or other political interference, inhibits organizational improvement based on reform of employment and training practices. Patronage and other political interference also causes instability in the work force and occasional massive turnovers in personnel. All of this contributes to low morale in the organization which in turn lowers efficiency.

In addition to the above physical and organizational difficulties, or perhaps because of them, maintenance has generated little professional interest from highway engineers and administrators. The process of maintaining a highway system has apparently not been as exciting as the processes involved in planning, design and construction.

Contributing to this lack of appeal is the general feeling of many highway engineers that operations and problems of maintenance are too varied and ill defined to be handled by a planned and scheduled approach using improved management techniques. As a result of this lack of professional interest, much highway maintenance is done with a minimum of systematic
organization and planning. Lack of planning tends to increase "emergency" repairs and rush work at the expense of planned maintenance. This further lowers overall efficiency.

The lack of professional interest has also existed in the field of research where, until recently, a relatively small effort had been expended on problems of highway maintenance compared to the effort devoted to questions of design and construction.

1.3.2 Conventional Approach

During the past ten years, efforts to find solutions to maintenance problems have increased. Most of this work has been directed toward improvement of technology or improvement of management. This has been the conventional approach.

When discussing solutions to a problem, one of the first things that occurs to an engineer is a solution based on improved technology. Technology has provided answers to many of our problems and we naturally look to improved technology first for solutions.

Advances in technology, however, have not yet been able to provide many dramatic solutions to the problems of highway maintenance. There is, of course, steady evolutionary progress in the machines available for maintenance use. Conventional equipment is generally superior in capacity, reliability and ease of operation to that in use only a few years
ago. In addition to improvement in conventional equipment, there has been a number of innovations that have lowered the cost of performing some maintenance activities. Specialized mowing machines for mowing steep slopes and under guard rails, faster drying traffic paint, herbicides, machines to pick up litter and other innovations have been found to lower costs in certain situations (7).

Most maintenance operations, however, have been performed in about the same way for several years. Many of these operations do not lend themselves to the application of highly mechanized or automated solutions. Although new machines or new methods of performing highway maintenance may offer some relief, it seems unlikely that major reductions in the cost of maintenance can be achieved this way.

Most of the recent effort to improve highway maintenance has been directed toward the management and planning of maintenance organizations. This work has attempted to either; improve the operational efficiency of maintenance organizations, or predict future maintenance requirements for budgeting or planning use.

These studies have sometimes resulted in improved maintenance management. However, they have dealt only with the third type of maintenance question: "How can maintenance operations be done most efficiently?" Little effort has been made to answer the first two questions which are the primary
concern of this study: a. what is the best balance between initial cost and maintenance cost and, b. how much maintenance should be done on existing roads.

1.4 GENERAL APPROACH

To answer the first two maintenance questions posed in section 1.1.2, requires proper analysis of the tradeoffs between maintenance on one hand and construction costs and user benefits on the other. This study treats highway maintenance as an integral part of the larger process of providing highway transportation. To better explain this approach, a short discussion of the general problem solving process as it relates to highway transportation may be useful.

Problem solving has been described as a five step process as follows.

1. Select goals
2. Devise promising alternative methods or strategies for achieving the desired goals.
3. Predict the significant behavior of each of the proposed strategies.
4. Evaluate the results of each strategy, as predicted in step 3, in relation to the selected goals.
5. Select the best strategy, or redefine goals as a result of information gained during steps 2, 3 or 4 and repeat process.
1.4.1 Selecting Goals

Selecting the goals for a highway system can be a complex and difficult problem. This is especially true in areas where the highway has a substantial and detrimental effect on environmental properties such as esthetics and air and noise pollution or causes disruption of social institutions. These effects are difficult or impossible to reduce to economic terms and their proper consideration represents a related field of study. However, for the low cost, two lane roads in rural settings which are of interest in this study, these environmental and social effects are less important. Air and noise pollution are usually far below objectional levels and the social effects of the road are usually considered beneficial instead of detrimental by the local population.

For this type of road, the proper goal for the system can usually be measured in monetary terms. There are several techniques that may be used for analyzing investments in engineering projects. The one selected for use in this study is minimum, present worth of transportation cost.

1.4.2 Devising Strategies

After goals have been selected, plans for reaching these goals must be proposed. In the case of highway transportation, plans for attaining the goals must include the location and
design of the roadway. It must also specify construction methods and timing, as well as maintenance policy. These overall plans for providing highway transportation will be called strategies in this thesis. This is to avoid confusion with the term, highway plan, which usually refers only to the details of initial construction.

Formulating alternative strategies for providing the system is obviously an important part of the problem solving process. The quality of the final solution will be no better than the quality of the best strategy evaluated. The rest of the problem solving process may be intelligently followed, but if only second rate strategies are considered, the solution selected will be second rate. The problem of strategy generation is a generally neglected area of highway design. Rigid design standards dominate and restrict the possibilities for solutions in many areas of highway design, construction, and maintenance. Governmental regulations further restrict the choice of strategies. Although this study does not address the problem of strategy formulation directly, the techniques developed for analyzing the highway problem are flexible enough to cope with a wide variety of approaches. It is hoped that this capability will encourage the consideration of strategies that include the use of new materials and methods for providing highway transportation.
1.4.3 Predicting System Behavior

Predicting the behavior of the proposed systems (step 3) is essential if the competing strategies are to be intelligently evaluated. Prediction of these consequences is a major concern of this study. Because of the complex interactions involved in the system, and the necessity for predicting behavior over extended time periods, a computer simulation model was designed to make these predictions.

This thesis is primarily concerned with the part of the model relating to the prediction of maintenance cost and the effect of maintenance on the overall performance of the system. The work reported here was developed concurrently with corresponding work by others on the prediction of construction costs and road user costs (8). The maintenance submodel developed during this study was programmed in conjunction with the submodels for construction and user costs to form a total cost model. The resulting model can be used in an iterative manner to investigate the consequences of any number of alternative strategies involving design variations, maintenance policies and the timing of construction and reconstruction.

In addition to use within the total cost model, the maintenance model may also prove useful for incorporation into other highway transportation models. These have been developed for various uses over the last few years and typically have only elementary subroutines for predicting main-
tenance cost. Incorporating a more realistic maintenance model would upgrade the performance of these models.

1.4.4 Evaluation and Selection

The steps of evaluation and selection in the general problem solving process become almost trivial if the goal is specified as providing highway transportation at the minimum, present worth, cost. However, other factors often need to be considered. Risk and uncertainty, limitations on resources, and administrative or political constraints are factors that sometimes influence decisions.

Various concepts and techniques have been devised for incorporating these factors into the decision process. One of the objectives of this thesis will be to show that the use of the maintenance cost model makes it practical to use some of these techniques in making highway transportation decisions. Examples of the application of the concepts of maintainability and decision theory are presented to show how these concepts can be used in conjunction with the maintenance model to improve the decision process.
CHAPTER II
REVIEW OF LITERATURE

Literature in several fields was reviewed during this study. Recent attempts to develop models for evaluating competing highway strategies, studies of highway maintenance and general highway research were reviewed to gather the information needed for model development. Some of the more useful findings are briefly discussed in this chapter.

2.1 MODELING OF HIGHWAY TRANSPORTATION

The maintenance model of this study was designed to function as part of an overall total cost model which also contains submodels for predicting the construction and road user costs. The purpose of this overall model is to assist in the evaluation of strategies for individual highway projects. Several models have been developed for similar purposes. Three of these influenced the design of the current model and will be discussed briefly.

Oglesby and Altenhofen (10) developed a model for selecting economical design standards for low volume rural roads in the U.S. These standards are for general use on low volume roads. This is a somewhat different objective than the evaluation of strategies for specific, individual projects; however, the problems involved in this study were similar to those of a project evaluation model.
The results of this study are presented as a series of figures where the construction, maintenance and road user costs are plotted as functions of roadbed width for several surface types and for two constant traffic volumes. The report contains a considerable amount of information concerning highway maintenance which was of value to this study.

Another model was designed by Lago (11) to select optimum technology for highway transportation, a goal similar to that of the present study. The structure and operation of this model is also similar to the overall model developed during the present study. The model is designed to be used iteratively and no optimizating procedures are included.

However, much of the study is devoted to selection of vehicle characteristics (type, power, payload, etc.). Another difference between Lago's model and the overall model described in Chapter III is in the handling of highway maintenance. Maintenance cost is predicted and included as part of the total cost, but since there is no provision for specifying or varying the maintenance policy, the tradeoffs involving maintenance can not be explored.

Lack et al. (12) designed a highway cost model based on experience with low volume roads in Australia. This model uses dynamic programming to find optimum strategies for specific individual projects. However, in order to keep the computer time and cost within reason, the simulation used by the
dynamic programming model had to be simplified. Many of the interactions between parts of the real system are not considered. Among these are the relationships between maintenance policy and user cost, maintenance cost and local conditions (haul distance, prices, etc.), and surface condition and traffic volume. Although these relationships are considered important, the simplifications and assumptions made in the Australian model are well thought out and reasonable.

All three of the above models contributed both ideas and maintenance data that were useful in the present study.

2.2 HIGHWAY MAINTENANCE LITERATURE

As mentioned earlier, most highway maintenance research has been aimed at either increasing the efficiency of maintenance organizations, or predicting future maintenance costs for budgeting or planning use. Although this thesis is primarily concerned with the broader problem of integrating maintenance into the overall process of providing highway transportation, study of this literature helped to develop an appreciation for the problems and operations involved. These studies also provided most of the usable information about deterioration rates, productivities, and maintenance methods necessary to construct the maintenance model.
2.2.1 Maintenance Management Studies

Most highway maintenance research has been devoted to general studies of the management and operation of individual maintenance organizations. These have ranged from studies of detailed methods and materials for individual maintenance operations to studies of overall management and long range planning for complete management organizations.

A substantial amount of work has been done to find efficient methods of doing individual maintenance operations. Time and motion studies have found that substantial time and cost savings can sometimes be made by changes in equipment selection, crew size, crew composition, and work procedures (13, 14, 15).

Other studies have focused their attention on the problem of effective management at the operating level. Attention has been given to planning and scheduling of work, effective maintenance of equipment, inventory control of materials, training of personnel and similar local management problems (16, 17). Some of these studies have made use of mathematical optimization and/or other management science techniques to find improved solutions for the different operations studied (18, 19).

The more general problem of management of the total maintenance organization has also been studied. In these, long range planning, budgeting, maintenance standards, per-
formance evaluation, and other problems of upper level management have been considered.

The usual objective has been to improve the performance of the organization. These studies typically include work on both the individual field operations and the broader organizational questions of planning, managing and recording maintenance activities. Recommendations as a result of this type of study range from proposed optimum mixes of men and equipment for individual operations to recommendations concerning planning, control, and reporting of work (13, 20, 21).

In addition, these studies often have provisions for putting their recommendations into practice. As a result, the studies have sometimes resulted in improvements in efficiency of the subject organization. Major decreases in required maintenance expenditure have been reported (16).

These studies, however, make little or no attempt to treat maintenance as part of the broader problem of providing highway transportation. Instead, they seem to be made on the implicit assumption that there is a given quantity of maintenance work to be done each year.

The only exceptions to this limited viewpoint have been a few attempts to deal with the question of maintenance policy by developing standard maintenance policies (22, 23). There is no indication, however, that formal analytical techniques have been used to determine these
policies. Instead, the judgment of the engineers involved seems to have been the only determinant.

Conventional maintenance studies typically collect a considerable amount of information concerning productivity rates, typical operating sequences, and maintenance methods. A variety of miscellaneous information incidental to maintenance operations is also usually gathered and often included as background information in these reports. These studies yielded otherwise unavailable information needed for designing the maintenance model.

2.2.2 Maintenance Cost Prediction Studies

Other highway maintenance studies are directed toward predicting future maintenance costs. A convincing method of predicting these costs is often needed to justify maintenance budgets to legislative bodies. This appears to have been the major impetus for this type of work. Some form of prediction is also needed for management planning use. These are apparently the two common reasons for work on maintenance cost prediction methods.

Most of the methods currently in use for estimating future maintenance costs are based on past, local experience and are usually no more than rough projections for estimating the next year's budget. However, recent maintenance studies have attempted to devise more reliable methods.
of predicting future maintenance requirements. These studies have resulted in a variety of mathematical equations or models for estimating highway maintenance costs.

The available methods of predicting maintenance cost can be divided into five categories (3):

1. Those which simply specify an annual maintenance expenditure per mile.

2. Those which recognize the influence of the type of road and thus predict cost per mile for a given type of road (3, 24).

3. Models that predict maintenance cost according to the type of the road and the volume of traffic. These models in general indicate a linear relationship between maintenance cost and traffic volume for different types of road (12, 6).

4. Models that predict maintenance cost as a function of design, operation, and climatic factors, but do not consider any interaction among these factors. These models are usually developed by use of regression analysis (26, 27).

5. Models that recognize interactions among the variables and attempt to determine which variables and combinations of variables have a
significant correlation with maintenance cost, using multiple regression analysis (28,20,30).

A more detailed discussion of the most interesting maintenance models is given in Appendix F.

As a result of this review it was concluded that none of the cost prediction models reviewed had been developed to help analyze the tradeoff opportunities between maintenance and other costs or benefits, and none are suited for this use. In addition to being unsuitable for use in tradeoff analysis, the existing models are valid only in the geographical area for which they were developed. All have biases built in to represent conditions in the individual study area. This is a necessary adjustment if the model is to be valid. However, most of these biases are incorporated into the basic structure of the model and there is no provision to adjust them for use under changed conditions. This is a serious drawback if the model is to be useful over a wide range of geographical and economic conditions.

Although none of the reviewed models are satisfactory for use in a comprehensive model to analyze design tradeoffs, they are the major source of information about the relationships between various design, traffic and environmental parameters and the resulting maintenance demand.
2.2.3 Prediction of Roadway Condition

Prediction of roadway surface condition during the analysis period is a key element in simulating system behavior as surface conditions affect both road user and maintenance costs.

Surface condition sometimes has a major influence on road user costs. This is especially true for earth and gravel surfaces or paved surfaces that have deteriorated substantially. The surface characteristics that may influence road user costs include roughness, rolling resistance and coefficient of friction (31).

Since maintenance costs will increase as surface condition deteriorates, predicting surface condition is also an integral part of predicting surface maintenance costs. Conversely, the surface condition, at any time, will depend on the maintenance policy that has been followed. Thus, prediction of maintenance cost and surface conditions are interdependent parts of the same problem. The surface characteristics that influence maintenance must be identified for each type of surface.

A technique or procedure for measuring surface condition in terms of the characteristics that affect road user and maintenance costs is needed for each type of roadway surface.
2.2.3.1 Paved Surface: Much of the recent study of pavement surface condition has used AASHO's Present Serviceability Index, PSI, as the measure of surface condition. The findings of these studies form a basis for developing the techniques needed to predict paved surface condition in terms of the characteristics that affect user and maintenance cost.

PSI was defined during the AASHO Road Test* as a subjective measure of the pavement's ability to serve traffic. Originally, a rating panel was used to judge serviceability. However, to avoid the need for a panel, multiple regression analysis was used to correlate these ratings with measurable features of pavement deterioration. The PSI of flexible pavement was found to be a function of longitudinal profile variations, rutting, and the amount of cracking and patching (32). Thus PSI provides not only a measure of the pavement's ability to serve traffic, but also a link to the physical measures of deterioration. These measures of deterioration are the surface characteristics that normally determine the need for maintenance of bituminous surfaces (22, 23).

The characteristic of paved surfaces that has the most effect on user cost is roughness (31, 33). Coefficient of

friction and rolling resistance normally have little influence (31,34,35).

Yoder and Milhouse (36) investigated the correlation between roadway roughness and PSI. The equations found showed close agreement for all of the common roughness measuring devices.

The studies mentioned above provide the means to relate PSI to the important surface characteristics that affect both road user and maintenance cost. The AASHO Road Test and the subsequent satellite tests and studies developed methods of predicting PSI as a function of pavement design and traffic load. Work by Konduer and Krizek (37) based on information from the AASHO test established a relationship between PSI drop and the factors of pavement design, axle loading and number of load applications.

The AASHO Road Test involved only one type of subsoil. However, the relationship between pavement deterioration and subsoil type has been extensively studied to determine pavement design methods (38,39).

Several studies have investigated the influence of other factors on pavement deterioration. Subsoil swelling and shrinking sometimes have an important effect on PSI (40). Aging of asphalt paving mixtures were found to become more susceptible to cracking with time (41,42).

As can be seen from the above discussion, PSI has been related to the design of the pavement, the loads that it
carries and the environment in which it operates.

2.2.3.2 Gravel and Earth Surfaces: Little quantitative information has been published on the behavior of gravel and earth roads. Some of the more useful information will be briefly discussed.

Since both road user costs and the need for maintenance are influenced by surface roughness, this is the logical surface characteristic to represent roadway condition. Rainfall, cross section design, and the type and gradation of surface material have all been mentioned as factors affecting roughness (43, 44). It is generally agreed, however, that blading frequency and traffic volume are the two principle variables that determine this surface characteristic.

No information was found to directly establish the relationship between roughness and frequency of blading. Two reports were examined that reported the range of roughnesses found on existing gravel and earth roads. These surveys were made in Kenya and Jamaica and the range of surface roughness found was similar for the two areas (33, 45). Roughness, and thus the need to blade, is often assumed to be a linear function of traffic, but there is little agreement about the actual relationship (10, 43). One U.S. study reported the frequency of bladings to be between 4 and 160 times per year (26). Another report based on African experience suggests blading every 1,000 - 1,200 vehicles (43).
Still another based on Western U.S. experience uses estimates varying between 3,500 to 9,000 vehicles between bladings (10).

Another aspect of gravel roads that must be simulated is loss of gravel under traffic and the periodic regraveling required. Information on the relationship between gravel loss and traffic volume is inconclusive. Several reports mention gravel loss, but the estimates of annual loss vary from 0.01" to 1.0" (43,46,47). Only three sources were found that comment on the relationship of gravel loss to traffic volume. One report claims there is no relationship (48). However, the range of traffic volume studies was very narrow and this conclusion appears unjustified. The second source lists the gravel loss and traffic columns observed on several roads but makes no attempt to find a relationship (49). The third report presents a linear plot of gravel loss versus traffic column that appears to be well supported by evidence collected in six areas of Virginia (13).

Much of the above information was used in the maintenance model developed during this study.
CHAPTER III

DISCUSSION OF ECONOMIC PRINCIPLES AND MODEL FRAMEWORK

Maintenance must be considered as part of the entire system, and the performance of that system must be evaluated if the fundamental questions of maintenance are to be answered. Minimization of total transportation cost is the evaluation method considered most appropriate for low volume roads. This study is an attempt to extend the capability to evaluate highway strategies to include consideration of the costs and effects of maintenance. This chapter will discuss some of the principles involved in this type of analysis and will attempt to put the problem of maintenance prediction in perspective as part of such an analysis.

3.1 DISCUSSION OF TRANSPORTATION INVESTMENT

Analysis of transportation investment opportunity requires a knowledge of both the supply and demand functions involved.

The supply or production of highway transportation is conceptually similar to other processes that produce goods or services. A production technique combines a variety of resources to produce highway transportation. A particular set of techniques and resources is referred to as a strategy. There are usually several strategies that can be considered for any situation. The problem is to determine
which one costs the least.

The lowest cost strategy can not be determined without knowledge of the present and future demand for transportation. How much transportation will be used at various prices must be predicted. Prediction of this demand function is, however, a separate and much studied problem which will not be discussed here.

This study is concerned with finding the lowest cost strategy for supplying highway transportation on an individual project with a given demand function. Before exploring alternative strategies for individual projects however, an attempt should be made to solve two broader problems of transportation investment.

The first problem is to determine what fraction of the total available resources should be spent on transportation, as opposed to other public investments. The need for transportation must be balanced against the need for other goods and services if the limited resources available to a country or state are to be used to best advantage. Additional projects should never be built in one sector if an opportunity for investment which will yield greater returns is being neglected in another sector.

The second problem is to determine the priorities of investment opportunities within the transportation sector. These should include priorities of the possible modes of transportation as well as priorities of projects within each
mode. Again the test is; "is there another potential project that will yield greater relative returns?"

Both of the above problems are more basic economic questions than strategy selections for individual projects and have been mentioned to give perspective to the work of this study. The focus of the study is, however, on the more narrow problem of strategy selection for the individual project. The broader aspects of economic evaluation will not be further discussed.

3.2 EVALUATION OF ALTERNATIVE STRATEGIES

As noted in Chapter I, a major portion of this study is devoted to developing simulation techniques to predict the costs and future behavior of alternative highway transportation strategies. Predicting the consequences of alternative strategies is however, only half of the problem of selecting the most efficient way to provide transportation.

Some evaluation method must be adopted that is capable of reducing the predicted time stream of costs to a measure that accurately reflects the relative desirability of the proposed strategies. As discussed in Section 1.4.1, minimization of total transportation cost is considered a satisfactory measure of desirability for the low volume roads of interest to this study.
3.2.1 Present Worth of Total Cost

Present worth of the total transportation cost, the measure of evaluation used in this study, is found by:

\[
TC'_x = \sum_{i=0}^{i=n} \frac{CC_{xi} + MC_{xi} + UC_{xi}}{(1 + d)^i}
\]  

(3-1)

where \( TC'_x \) is the present worth of the total cost for strategy \( x \) over an analysis period of \( n \) years; \( CC_{xi}, MC_{xi}, \) and \( UC_{xi} \) are respectively, the construction, maintenance and user costs predicted for year \( i \) using strategy \( x \); and \( d \) is the discount rate or opportunity cost of capital.

By this method, the strategy with the lowest present worth of total transportation cost is preferred. This is a valid method for economic comparison of alternative strategies if the traffic demand is perfectly inelastic. That is, if a fixed number of vehicles are going to use the road, irrespective of its design or maintenance, then the total cost of that quantity of transportation should be minimized. For this case, the quantity of transportation produced and the benefits are the same for all competing strategies and need not be explicitly considered.

The assumption of a perfectly inelastic traffic demand function may approximate reality in some cases, but it is not the general situation. The amount of traffic that will use a particular road is determined by the cost to the road user.
A poorly maintained earth or gravel road built on a winding alignment with steep grades, causes high road user costs that tend to discourage use of the road. As user costs increase, other roads and even other modes of transportation become more competitive. Even in the extreme case where the road is the only means of transportation between two points, high road user costs will discourage travel. Goods which might have been transported to market at a profit will not be produced if transportation costs make their production unprofitable.

The simple measure of total present worth cost is not valid if the traffic varies with user costs (traffic demand function that is not perfectly inelastic). When comparing two strategies by the total cost method, the respective construction and maintenance costs can be compared without complication. But it is not valid to compare the computed user costs if traffic volume is not the same for both strategies. The fallacy of comparing user costs for different traffic volumes can be seen by considering the case where lack of maintenance results in an impassable road. This eliminates road user costs completely and results in a low total cost, but is presumably not the best solution.

3.2.2 Willingness to Pay

In order to compare alternative strategies when the traffic demand function is not perfectly inelastic, the concept of willingness to pay is introduced. Willingness to pay
is a method of measuring benefits so that lost benefits can be included in the cost thus avoiding the above fallacy. A short discussion of the supply and demand relationships of traffic will be used to explain the concept of willingness to pay and its use in strategy evaluation.

The idealized demand curve shown in Figure 3-1 as CD indicates the number of vehicles that will travel between two points as a function of the user's perceived price of travel.

Figure 3-1: Illustration of Willingness to Pay and Consumer Surplus
The supply curves for two strategies are labeled 1 and 2. These represent the perceived price the user must pay (perceived user cost) as a function of traffic volume for each strategy. For strategy 1, the supply and demand curves intersect at point E. Thus $V_1$ vehicles use the road and each will have to pay the price $P_1$ in user costs. This results in a total cost to users of $(P_1)(V_1)$. This is represented by the area GEHO in Figure 3-1. However, by definition, the demand curve is a representation of willingness to pay. Most of the users in volume $V_1$ would have been willing to pay more than the actual price, $P_1$. The last user to make up the volume $V_1$ is represented in the demand curve at point E. He paid exactly what the trip was worth to him. All the other users paid less than the trips were worth to them. The price they would have been willing to pay is represented by the portion of the demand curve between E and C. Presumably, the vehicle that wanted to use the road the most would have been willing to pay up to price $P_0$. The difference between the total that users would have been willing to pay, $CEHO$ and what they actually paid, $GEHO$, is called consumer surplus, area $CEG$. Since this is a savings to the users of the system, it is usually considered a user benefit in economic analysis (50).

If the same procedure is followed through for strategy 2, the user cost paid is represented by area $FJOI$, willingness-
ness to pay is area CFJO, and consumer surplus is area CFI.

When comparing alternative strategies, the analyst is interested in the differences in costs and benefits. In the example shown, Strategy 2 can be considered to have a net user benefit relative to strategy 1 equal to the change in consumer surplus. This is shown as the shaded area EFIG in Figure 3-1. The change in consumer surplus is used as the measure of net road user benefit for this study.

Change in consumer surplus, EFIG is the difference between areas GEFJO and FJOI. FJOI represents the total user cost paid for strategy 1 plus EFJH. Areas CEHO and CFJO have been shown to represent the total amounts that users are willing to pay at prices $P_1$ and $P_2$ respectively. EFJH is thus called the change in total willingness to pay, when going from strategy 1 to strategy 2. Therefore change in consumer surplus between two alternative strategies is:

$$\Delta CS_{ij} = UC_i + \Delta WTP_{ij} - UC_j$$

or

$$\Delta CS_{ij} = UC_i - (UC_j - \Delta WTP_{ij})$$

where:  
$\Delta CS_{ij}$ = Change in consumer surplus when changing from strategy i to strategy j  
$UC_i$ = Total user cost for strategy i  
$UC_j$ = Total user cost for strategy j  
$\Delta WTP_{ij}$ = Change in willingness to pay when changing from strategy i to strategy j.
Thus when comparing two strategies, based on change in consumer surplus, $\Delta WTP$ should be subtracted from the user cost of the strategy giving the lower road user costs. For example to compare strategies 1 and 2, the following total present worth costs should be compared.

\[
TC_1' = \sum_{i=0}^{m} \left[ \frac{CC_{1i} + MC_{1i} + UC_{1i}}{(1 + d)^i} \right]
\]

\[
TC_2' = \sum_{i=0}^{m} \left[ \frac{CC_{2i} + MC_{2i} + UC_{2i} - \Delta WTP_{12}}{(1 + d)^i} \right]
\]

This is the method used in this study.

### 3.2.3 Miscellaneous Economic Considerations

There are several other factors that must be dealt with for the successful analysis of highway investment. A few of the more important of these factors will be briefly discussed in this section.

**3.2.3.1 Time Value of Money:** Money has the ability to earn income over time. This must be recognized and accounted for in any valid comparison of strategies. This is usually done by applying a discount rate to the costs and benefits produced by the analyzed project. In this study, all costs or benefits are reduced to their present worth value by the standard present worth formula:

\[
PWC = \frac{AC}{(1 + d)^V}\]

(3-6)
where: \( PWC = \) present worth cost
\( AC = \) actual cost
\( d = \) discount rate
\( YR = \) year of analysis period in which costs are incurred.

Selection of an appropriate discount rate is an important part of the analysis. Unrealistically high or low discount rates can substantially change the predicted present worth values, and thus affect project rankings. This is particularly important when the strategies being compared involve major tradeoffs between immediate and deferred costs, since the discount rate affects only the present value of the deferred costs. The tradeoff between construction costs on one hand and maintenance and user costs on the other is this type of situation and the proper choice of discount rate is crucial to a realistic analysis.

Economists do not agree on how the discount rate for public investment should be selected. However, there seems to be some agreement that the proper rate is somewhere between the market rate of interest minus an allowance for inflation and the opportunity cost of capital in the private sector of the economy. The opportunity cost for private investment is usually much higher than the market rate of interest because of corporation tax. For example, the current tax rate for most U.S. corporations is 50 percent.
At this tax rate, the before tax rate of return for investments must be twice the market cost of money to break even.

To avoid inefficient allocation of resources between the private and public sector it seems reasonable to require that public investments produce returns equal to the private sector. However, not all private investment is taxed at such a high rate. As a result, individuals, partnerships, etc. presumably make investments that yield only little more than the market cost of capital. Because of this, and other complications discussed in the references (51, 52, 53) the appropriate discount rate for public investment should probably be between the market cost and the corporate opportunity cost of capital.

The discount rate must also be adjusted to allow for any inflation that is expected to occur during the analysis period. If the costs and benefits used in the analysis are predicted at current prices, the actual costs and benefits will be greater if prices inflate during the analysis period. This tends to offset the effect of the discount rate in the present worth computations. The expected average annual inflation rate should be subtracted during the computations for selecting the discount rate.

3.2.3.2 Risk: Two aspects of risk should be considered. One is related to the uncertainty of the predicted future costs and benefits. The second is the natural aversion of
most people, firms, governments etc. to taking risks. Both of these aspects of risk are sometimes implicitly accounted for by increasing the discount rate used in the analysis. However, there is no systematic way to make this adjustment; and once it is made, it obscures the cost associated with risk.

More appropriate ways of incorporating both aspects of risk into the analysis will be discussed in Chapter VII, where example problems show how the model can be used with decision theory to systematically approach this problem.

3.2.3.3 Economic Costs: To predict the costs needed for minimum cost analysis, the needed quantities of resources (labor equipment and material) are first estimated. These must be converted to monetary costs before comparison of alternatives is possible. To convert quantities to monetary costs requires unit costs for the various resources needed. These should reflect the real costs to the economy. Proper selection of these unit costs is an important consideration in economic analysis.

Market prices are often used to convert quantities of resources to costs. Local wage rates, equipment rental and material prices can be used. However, market price is not always a suitable measure for converting labor, equipment and material to economic costs. There may be a substantial difference between market price and the cost to the economy.
Cost of labor is an example. Wages paid in an area of high unemployment may be far above the cost to the economy since this labor force would have been wasted and possibly supported by welfare payments if not employed. Other factors which often distort market prices are taxes, subsidies and monopoly pricing. Common taxes that distort the market price of transportation are fuel taxes and vehicle import duties.

In order to find the most economical tradeoff between various resources the economic cost must be determined and used in the analysis. The prices used in place of market prices are called shadow prices. Determination of these shadow prices is beyond the scope of this study. The model is constructed to allow the unit prices to be specified by the model user. Either simple market prices or, more difficult to determine, shadow prices can be used depending on the level of sophistication of the analysis.

3.2.3.4 Analysis Period and Salvage Value: At current, realistic discount rates the problems associated with length of analysis and handling salvage value are usually not critical. Costs incurred and benefits accrued in the future become much less important than those of the first few years of the analysis period.

For example, for a relatively short analysis period of twenty years and a discount rate of eight percent, the present worth value of a cost incurred in the twentieth year is
about one fifth (.218) of an equal cost incurred at the
start of the period. For a twenty five year period and a
discount rate of ten percent the effect of an end of period
cost relative to an equal cost at the start shrinks to less
than one tenth (.092).

The uncertainty of the prediction of cost or salvage
values twenty or twenty five years into the future further
diminish the emphasis that should be placed on these figures.

The combination of these two factors indicates that the
forty and fifty year analysis period sometimes advocated are
unnecessary for all but the unusual situation. (The present
worth factor for forty years at eight percent is 0.046, a
reduction factor of over twenty.)

Since the difference in salvage values of alternative
strategies is not expected to be significant in the usual
situation, the model does not consider salvage value in the
predicted total cost. However, in some analyses a signifi-
cant difference in salvage value may be likely. The most
usual situation in which this happens is where one of the
strategies being compared includes major reconstruction work
near the end of the analysis period. If a significant dif-
ference in salvage value is expected, this difference can
easily be incorporated in the evaluation by the analyst. In
any case, determination of salvage value rests on the judge-
ment of the analyst and is clearly beyond the scope of the
current model.

3.3 FRAMEWORK OF THE TOTAL COST MODEL

The present worth of the total cost of transportation, as defined by equation 3-1, is found by predicting and discounting the construction, maintenance and road user costs incurred over an appropriate analysis period. The length of the analysis period will usually be approximately twenty to twenty five years as discussed in Section 3.2.3.4.

Although principally concerned with maintenance cost prediction, this study is part of a larger study directed toward prediction of the total transportation cost. The framework and operation of the total cost model will be briefly discussed to clarify its operation and the operation of the maintenance model within this larger model.

The total cost model consists of three individual submodels, programmed within the overall model framework. These submodels predict the construction, maintenance, and road user costs which make up the total cost. The operation of the overall model is straightforward. A flow chart of the cycle of operation is shown in Figure 3-2.

To examine a series of proposed strategies for a given project, the steps shown in Figure 3-2 are followed. Input variables define the project to be analyzed. Length, terrain, soil, climate, traffic demand, discount rate, and local unit costs for labor, equipment and materials are specified.
1. Input Background Information for Project

2. Input Specific Construction-Maintenance Strategy to be Evaluated

3. Construction Model Estimates Construction Cost


5. User Cost Model Estimates User Cost for Year

6. Main Routine Prints Out Construction, Maintenance and Road User Costs for Year and Computes and Prints out Accumulated, Discounted, Totals for Analysis So Far

Go To Next Year

Last Year of Analysis

Yes Try Other Strategy

Yes

No

End

Figure 3-2: Operation of The Total Cost Model
Other input variables define the construction and maintenance strategy to be tried. Grade, alignment, widths, depth of surfacing, maintenance policy, and reconstruction schedule are defined.

Based on this information the submodels within the total cost model estimate the construction, maintenance, and user costs for each year of the analysis period. This is done in the sequence shown in Figure 3-2. The model totals and discounts these costs to find the present value of the total transportation cost for the strategy specified. This allows the model user to evaluate a series of strategies on the basis of their predicted total cost.

This cycle of operation, although simple, allows the submodels to interact with each other to simulate the physical relationships between construction, maintenance, and traffic that were discussed in Section 1.1.3. By making the individual cost predictions year by year during the analysis period the submodels are able to base their annual predictions partly on information generated by the other models. Using this method, some of the feedback characteristics of the physical system can be simulated. The prediction of maintenance cost and roadway condition for each year is influenced by the volume and type of traffic predicted for that year by the user cost model, as well as by the description of the roadway from the construction model. The user
cost model in turn estimates individual vehicle costs for each year as a function of the roadway conditions predicted by the maintenance model and the physical description of the road.

Roadway condition is estimated by the maintenance model in terms of roughness, coefficient of friction and rolling resistance. The curvature and grade of the roadway are specified during construction or reconstruction. These are the input variables used by the user cost model to determine the perceived cost of operating each vehicle type. This perceived cost of operation is then used with the specified traffic demand function to predict the traffic volume for the year. Thus both user costs and traffic volumes are influenced by the predictions of the maintenance model.

By using this mode of operation, the overall model framework can simulate the major interaction between construction, maintenance and use of the road. Instead of attempting to make independent estimates of the construction, maintenance and user costs for the analysis period, estimates are based on the simulated behavior of the road during the analysis period.

Conventional project evaluation is usually based on estimates of construction and user costs. The total cost model developed during this study not only makes it possible to incorporate maintenance into the evaluation, but also
takes into consideration the effects of interaction between construction, maintenance and use.
CHAPTER IV
THE MAINTENANCE MODEL

The maintenance model discussed in this chapter forms the central part of the study. As discussed in the last chapter, using the maintenance model as an integral part of the total cost model allows future maintenance costs to be considered as a design parameter. In addition, the capability of estimating future maintenance costs allows the question of maintenance policy to be analytically explored. This capability also opens the way to the use of improved decision making concepts such as maintainability and decision theory.

This chapter discussed the problem of predicting maintenance costs and roadway condition. This problem is discussed in more detail in Sections 4.1 through 4.4. Section 4.1 discusses the basic concepts underlying the problem of predicting deterioration and explains why the approach used in this study was chosen. Section 4.2 outlines the basic objectives and general structure of the maintenance model. Section 4.3 contains a brief narrative description of each subroutine in the maintenance model, and Section 4.4 includes a detailed description of the derivation of the pavement maintenance subroutine to illustrate the way the model was designed.
4.1 METHODS OF PREDICTION

In order to predict the maintenance costs and roadway condition during the analysis period, the future behavior, including deterioration, of the proposed physical system must be predicted. Prediction of this behavior for future conditions of environment, load, and maintenance policy is a central part of the current maintenance model.

The variables that influence the behavior of a system are all of a random nature whether they are associated with environment, load, maintenance policy or the system itself. Therefore, any predictions of system behavior should ideally be made by a probabilistic model that takes the uncertain nature of these variables into consideration. However, the small amount of information available on many of the variables did not seem to justify the additional sophistication of a probabilistic model. Instead, the advantages of simplicity and economy of a deterministic model were chosen for this study. The current model uses average values of variables and predicts maintenance cost and roadway condition in terms of point estimates. The choice of this simpler type model allowed additional attention to be focused on other important aspects of the study.

There are two extremes to the possible approaches for predicting physical deterioration of the system.
a. One may be called the physics of failure approach. This method involves prediction by mathematical analysis, based on the physical characteristics of the facility, environment, loads and maintenance actions.

b. The other extreme is called the historical data method. Prediction is based on historical behavior of the same or similar facilities under similar conditions of environment, load and care.

The following paragraphs will discuss the strengths and weaknesses of each extreme method and explain the compromise method used in this study.

4.1.1 Physics of Failure

The physics of failure approach is conceptually much more appealing and potentially much more versatile than the historical data approach. Ideally, the physics of failure method should be able to accurately predict future performance based on the physical description of the facility, environment, loads and maintenance policy. Further, the behavior of completely new designs and materials could be predicted if this method were useable. However, the use of the physics of failure method, in its pure form, requires that all the applicable failure modes be thoroughly understood. Since this is not usually true, it is almost never possible to use this extreme method. Some compromise in-
volving the use of historical data is always necessary.

4.1.2 Historical Data Method

At the other extreme, a pure historical data or empirical approach requires the construction and testing of full scale prototypes under the applicable conditions of environment, load and repair. These requirements can sometimes be met in the case of relatively simple items that have been made and used in large numbers, if accurate records of their service life are available. Thus, it may be quite possible to predict the future behavior of a light bulb using only historical information, and no understanding of light bulbs if:

(a.) the light bulb is of the same design, materials and manufacturing methods as the bulbs on which the historical data was collected, and (b.) the bulbs are used under the same conditions of environment and load as those providing the historical data. These constraints can obviously place serious limitations on the use of this method.

For more complicated facilities used in small numbers under a variety of loads and environments, (such as most facilities of interest to civil engineers) the pure historical data approach is even less likely to be practical. The small sample size and the many poorly understood failure mechanisms result in data that is difficult to interpret and apply, even to relatively similar, proposed facilities. This method
is even less suited for predicting the behavior of new designs or materials. Nor is it suited to situations involving the behavior of conventional designs and materials if these are to be used under radically different conditions of environment, load and maintenance.

4.1.3 Approach Used

Since the failure mechanisms are not fully understood, and it is impractical to build and test full scale prototypes; neither of the extreme methods discussed above is a practical method for predicting overall highway deterioration. An approach that combines techniques from both methods appears to be the most promising. In this study, the behavior of the individual subsystems are predicted by the method that seems most appropriate. This depends on the techniques and information that are available for each subsystem. No attempt is made to use a uniform method for all situations.

Since the physics of failure approach offers the possibility of coping with new designs, materials, loading conditions and maintenance policies, this approach is employed as much as possible. However, since most of the important failure modes that determine the behavior of highway systems are not well understood, and since the mathematical relationships needed for prediction are only in the early stages of development, this study depends heavily on historical data
for predicting future behavior.

Prediction methods are applied to the finest practical breakdown of individual subsystems or components. These results are then combined within a systematic framework to simulate the behavior of the overall system. Thus, the overall prediction method used is a combination of the physics of failure and historical data methods, with each method being applied when it seems most applicable.

4.2 OBJECTIVES AND GENERAL STRUCTURE OF THE MAINTENANCE MODEL

4.2.1 Objectives

To function effectively within the total cost model the maintenance model must predict:

a. Maintenance cost, and

b. Roadway condition.

These must be predicted for each year of the analysis period as a function of design, environment, traffic volume, and level of maintenance. Maintenance cost affects the total cost directly. Roadway condition has an indirect effect through its influence on road user costs. To be generally useful, the model must make these predictions for a wide variety of designs, environments and traffic loads.
4.2.2 Structure of Model

To predict maintenance costs and roadway conditions for a wide range of situations requires a model that simulates the physical relationships involved. These relationships should be simulated in sufficient detail to allow the model to respond realistically to changes in design, environment, loads and maintenance policy. It was decided that the overall relationship between these variables and the resulting prediction of maintenance cost and roadway condition should be broken down into more easily understood subrelationships.

The framework that evolved corresponds to the basic physical relationships that exist in the sequence of events from deterioration to repair. These fundamental relationships are shown diagrammatically in Figure (4-1).

The function shown in $F_1$ represents the deterioration rate of the highway. The deterioration rate is affected by four types of variables:

1. Environment (climate, soil etc.)
2. Loads imposed on the system (traffic volume or number of equivalent loads)
3. Design of the system.
4. Level of maintenance (maintenance policy).

Rate of deterioration can be measured by such quantities as; amount of cracking, number of potholes, cubic yards of soil deposited in ditches, and inches of vegetation growth.
Input Parameters of Load, Environment & Design
(climate, traffic soil, design & maintenance stds, etc.)

\[ F_1 \]

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

\[ F_2 \]

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

\[ F_3 \]

Maintenance Input Required
(labor, equipment and materials)

\[ F_4 \]

Cost of Maintenance
(dollars per mile)

Figure 4-1: Relationship Between Parameters and Cost
This relationship, \( (F_1) \), is the part of the maintenance model most difficult to predict accurately.

Function \( F_2 \) in Figure 4-1 is the relationship between the extent of deterioration discussed above and the quantities of maintenance action expended as a result of this deterioration. Maintenance action can be measured by; tons of patching material placed, acres moved, square yards of area bladed etc. \( F_2 \) type relationships depend heavily on the maintenance policies and procedures being used. For instance, the area of pavement sealed may be much less than, equal to, or much greater than the area cracked depending on these policies. Finding the function to accurately represent this relationship is closely tied with the problem of selecting and specifying maintenance policy. In the current model it is possible to adjust the function to meet local conditions. It also makes it possible to explore the effects of various maintenance policies.

Function \( F_3 \) in Figure 4-1 determines the expenditure of maintenance effort needed to accomplish the maintenance action found by the model. Maintenance effort is measured in terms of labor, equipment and material in the current model. Finding \( F_3 \) type functions between actions needed and effort required is essentially a problem of measuring the productivity rates for the various operations.
The $F_4$ functions are the appropriate unit prices for labor, equipment and material for the location involved. The proper selection of these unit prices is discussed in Section 3.2.3.3. This is a separate problem in itself, however, the model allows the model user to specify the unit prices based on the best available information. Either market prices or, more difficult to determine, shadow prices can be used.

A fairly complex framework is needed to provide the level of detail shown diagrammatically in Figure 4-1. The four functions shown must be determined for each type of deterioration to be analyzed. This results in a model that is too large and complex for manual use. As a result of this complexity, the model was developed as a computer simulation which allows the construction of a complex, but still manageable model.

4.3 DESCRIPTION OF MODEL OPERATION

The structure of the maintenance model is designed to deal with four categories of maintenance, plus a section that sums the quantities of labor, equipment and materials and finds the monetary costs. For each of the four categories of maintenance activity (surface, drainage, shoulder, and vegetation control) the model explicitly represents the types of physical relationships defined in Figure 4-1. That is,
the model deals with the problem of finding deterioration, quantity of work, required input, and finally monetary cost, as individual parts of the actual physical sequence. The operation of the model is illustrated by the flow chart in Figure 4-2.

The four categories of maintenance simulated by this model often account for almost all the maintenance effort on low volume roads. The major exception is in locations where a substantial effort is required for snow removal. Snow removal does not normally involve physical deterioration of the system and presents a different type of tradeoff opportunity than the types of maintenance simulated. It can be thought of as a separate type of maintenance problem. In addition, many of the roads of interest to this study are in areas where snow removal is not required. For these reasons, snow removal is not handled in the model.

The model computes only the direct costs of doing the maintenance work. The administrative and overhead costs involved in the operation of the maintenance operation are not predicted. Investigation of the social, political and organizational factors that influence these costs is beyond the scope of this study. If these costs are needed for the analysis, they must be determined by the model user based on knowledge of the maintenance organization involved. Once determined, they may be easily added to the direct costs.
Figure 4-2: (page 1) Flow Diagram of Maintenance Model
SHOULDERS

Predict deterioration

Predict maintenance actions

Find maintenance inputs

Find maintenance costs

VEGETATION CONTROL

Input maintenance actions

Find maintenance inputs

Find maintenance costs

COST SUM ROUTINE

Totals quantities of Labor, Equipment and Materials by type

Multiplies total of each quantity by unit cost

Find total cost of Labor Equipment and Material

TO USER MODEL

Figure 4-2 (page 2): Flow Diagram of Maintenance Model
predicted by the maintenance model.

The maintenance model is made up of approximately 800 Fortran statements. Because of this size, a detailed line by line explanation is not practical. Instead, the basic structure and operation of each of the subroutines is described. In addition to this description, a detailed, equation by equation, description of one part of the model (pavement maintenance) is given in section 4.4 to illustrate in detail how the model was designed. The actual listing of the model is included in Appendix E, and a comprehensive list of definitions and assumptions on which the model is based is included in Appendix D.

The description in this section will be broken down into four parts, each dealing with an individual part of the maintenance model.

4.3.1 Surface Maintenance

The model has routines for paved, gravel and earth roads. The operation of these routines will be explained in this subsection.

4.3.1.1 Pavement Maintenance: Paved surface maintenance is handled in the model by a routine that simulates the cycle of deterioration and repair of an asphalt pavement for each year of the analysis period.
AASHO Present Serviceability Index, PSI, is used as a general measure of the surface condition and a typical variation of PSI as a result of deterioration and repair over a period of years is illustrated in Figure 4-3.

![Graph showing the variation of PSI over time with routine maintenance and resurfacing](image)

Figure 4-3: Example of How PSI Varies as a Result of Deterioration, Routine Maintenance, and Resurfacing

Simulation of this behavior is done in the five steps shown in Figure 4-2 as follows.

a. Deterioration is predicted for one year as a function of, traffic loads, pavement characteristics, and
environmental conditions, (F₁ type function in Figure 4-1). Deterioration is initially predicted in terms of PSI by a separate subroutine named DETER. This annual deterioration is then converted into units of Slope Variance, SV, Rut Depth, RD, and area of Cracking and Patching, (C+P) by using the predicted correlation between these physical measures and PSI.

b. The amount of maintenance work to be done during the year is determined as a function (F₂ type) of the predicted physical measures of deterioration [SV, RD & (C+P)] and the maintenance policy specified. The maintenance policy is selected by the model user and specifies what maintenance should be done for different degrees of deterioration. The model user has four variables with which he can specify a wide range of policies. (Detailed definitions of these maintenance policy variables are given in Appendix D.)

c. Based on the amount of maintenance to be done, the model computes the quantities of labor, equipment and material necessary to do the work (F₃ type function). This function is essentially an estimating procedure based on productivity rates determined during the review of literature. The definition of these variables and the values used in the model are given in Appendix D. These values can be
easily changed by the model user if he has additional information, or knowledge of non-typical or local conditions than would affect the validity of results.

d. After the quantities of labor, equipment and material have been determined, the model computes the expected monetary maintenance cost by use of the appropriate unit costs which have been furnished by the model user (F4 type functions).

e. In addition to the above cost prediction, the model must also predict the improvement in surface condition caused by maintenance if the behavior of the surface is to be simulated as in Figure 4-3. This is done by predicting the probably changes in the physical measures of slope variance, rut depth and area of cracking and patching and then converting these changed values into a changed value for serviceability.

f. In order to be compatible with the concurrently developed user cost model within the total model framework discussed in section 3.3, the model must also make yearly estimates of the pavement condition in terms of roughness, coefficient of friction and rolling resistance. Roughness is estimated as a function of serviceability. Rolling resistance is assumed to be constant. Coefficient of friction is estimated as a function of age of surface and
This cycle of operations involving annual estimates of maintenance cost and surface condition is made for each year of the analysis period.

4.3.1.2 Gravel Surface Maintenance: The maintenance of gravel surfaces is simulated in a different manner than paved surface maintenance. Blading is the primary type of maintenance for gravel surfaces. The frequency of blading is specified by the model user as either a function of time (blading per year) or a function of traffic (vehicles per blading). Both maintenance cost and surface conditions are based primarily on the frequency of blading.

Maintenance cost is computed by a series of steps similar to the steps F\textsubscript{2} through F\textsubscript{4} in Figure 4-1. Frequency of blading is specified by the model user. Thus, the maintenance cost estimate is not dependent on estimated deterioration. Instead, by using the specified frequency, traffic volume, and width of surface the model computes the area to be bladed per year. Finding the labor, equipment, and material needed and later the monetary cost is generally the same as the comparable steps for paved surface maintenance. The assumptions used in these calculations are given in Appendix D.

Surface condition is computed as function of frequency of blading and volume and type of traffic. It is assumed that
gravel surface condition is not affected by the age of the surface as long as enough gravel remains to prevent vehicles from breaking through the surface during wet weather.

In addition to blading, the maintenance cost for replenishing the gravel surface is also estimated if regraveling is specified as part of the maintenance policy. The gravel lost from the surface each year is computed as a function of the total weight of vehicles using the road during the year. This loss is subtracted from the remaining gravel layer each year and when the depth of gravel becomes less than a specified amount the regraveling routine is activated if regraveling is specified as part of the maintenance policy. The regraveling routine estimates the labor, equipment, and material needed to add a layer of compacted gravel to the surface. The detailed assumptions governing this operation are given in the section concerning regraveling in Appendix D.

If regraveling is not specified as part of the maintenance policy, the model assumes that the road reverts to an earth road when the remaining gravel layer becomes less than the minimum thickness required to support traffic. The model then converts the road type designation to earth and the remainder of the analysis will be made on the assumption that the road has an earth surface.

4.3.1.3 Earth Surface Maintenance: The maintenance of earth surfaces is the same as gravel surface maintenance ex-
except for the regraveling operation. The major difference between gravel and earth roads, as defined in this study, is that while gravel roads are assumed to remain passable all year, earth roads become impassable for some fraction of the year.

An effort was made during this study to find a reliable way to predict the fraction of the year that an earth road would be passable. This could reasonably be expected to be some function of: soil type, rainfall, type of vehicle used, maximum weight of vehicle, grades of road, and maintenance policy in effect. However, very little information could be found to help determine this relationship. If rolling resistance and coefficient of traction could be predicted for earth roads under adverse conditions, it might be possible to predict when the road would become impassable using the vehicle behavior routines in the user model. But realistically predicting rolling resistance and coefficient of traction under these conditions appears to be impractical. As a result, it was concluded that the most realistic way to determine the fraction of year that an earth road was likely to be impassable is based on the behavior of similar roads in the area. This fraction is supplied by the analyst in the current model.
4.3.2 Drainage Maintenance

The cost of drainage maintenance is predicted by a series of calculations that follow the general sequence illustrated in Figure 4-2. Rainfall, terrain, and slope steepness were the variables that could be identified in the literature as affecting the amount of sediment deposited. The model estimates quantity of sediment as a function of these three variables.

After the deposited sediment is estimated, the model determines how much will be removed by maintenance forces each year. The quantity removed is estimated as a function of the sediment deposited and specified maintenance policy.

The required input of labor equipment and material and the monetary cost of these inputs are estimated by a procedure similar to the corresponding steps for surface maintenance. The detailed assumptions governing this estimating procedure are given in Appendix D.

4.3.3 Shoulder Maintenance

Shoulder maintenance depends on the type of shoulder involved. Paved and unpaved shoulders are handled by different routines within the model.

Maintenance for paved shoulders is estimated as a function of the maintenance required on the roadway and the width of that roadway. The detailed assumptions are given in Appendix D.
Maintenance for unpaved shoulders is estimated as a function of traffic volume and width of traveled roadway. A minimum of one blading a year is also assumed in order to simulate minimum maintenance required to avoid direct damage to traveled surface from erosion, encroaching vegetation, etc.

4.3.4 Vegetation Control

Vegetation control is not usually a major part of maintenance cost in most areas. For this reason, the routine that estimates this cost is somewhat simpler than the other routines. No attempt is made, in the model, to estimate vegetation growth (which is the measure of deterioration in this case). Instead, the number of mowings to be done each year is specified by the model user based on his judgment and knowledge of the area. The amount of labor, equipment and materials required and their monetary cost is estimated by the model. These costs are estimated as a function of number of mowings per year, width to be mowed. The assumptions on which this function is based are given in Appendix D. Incidental work connected with vegetation control such as tree trimings at curves, reseeding and watering, removing of trees after windstorms, etc. is assumed to be absorbed in the cost calculated for mowing.

After costs for these four types of maintenance are estimated, the model totals the costs of labor, equipment and
material. The totals are then discounted to present worth values. These totals, both discounted and actual, are then used by the main subroutine to complete the accumulated total costs for the analysis.

4.4 DETAILED DESCRIPTION OF PAVEMENT MAINTENANCE SUBROUTINE

This section illustrates the step by step development of the pavement maintenance routine as an example of the development of the model.

The pavement maintenance routine was chosen since it fully illustrates the basic approach used in the model, i.e. the approach shown diagrammatically in Figure 4-1.

4.4.1 Deterioration Prediction

Deterioration is predicted as a drop in AASHO Present Serviceability Index, PSI, for each year of the analysis period. The model estimates deterioration as a function of equivalent axle loads, pavement characteristics and environment. The equation for estimating deterioration was developed from a regression analysis of AASHO Road Test Results by Konduer and Krizik (37). Since the model is to be used over a range of conditions, the equation found in their study was modified to allow adjustment to local conditions. The basic equation that resulted was of the form:

\[ \Delta PSI = KxSxV \]  \hspace{1cm} (4-1)

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

The slope of the deterioration rate, $S$, can be approximated by the following equation (37):

$$S = \alpha 10^{-\beta \overline{SN}'}$$  \hspace{1cm} (4-2)

where $\alpha$ and $\beta$ are dependent on $P$, the equivalent single axle load used, as follows (37):

$$\alpha = 0.5 \times 10^{0.078P-6}$$  \hspace{1cm} (4-3)

$$\beta = 0.35 + 0.005P$$  \hspace{1cm} (4-4)

and $\overline{SN}'$ is the effective structural number, or thickness index of the pavement. This is found by adjusting the actual thickness index, $SN$, to take subsoil quality into consideration (38):

$$\overline{SN}' = \frac{\overline{SN} \log(CBR_1)}{\log(CBR_0)}$$  \hspace{1cm} (4-5)

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

$$\overline{SN} = a_1D_1 + a_2D_2 + a_3D_3$$  \hspace{1cm} (4-6)

$D_1$, $D_2$, and $D_3$ are the depths of the component layers of the pavement. The coefficients $a_1$, $a_2$, and $a_3$ are weighting
factors (function of strength) for the corresponding layers. The values found during the AASHO Road Test are used for these coefficients. CBR₁ is the California Bearing Ratio of the subsoil of interest. CBR₀ is the California Bearing Ratio of the subgrade soil used in the AASHO Road Test, on which these relationships are based.

Substituting equations 4-3, 4-4 and 4-5 into equation 4-2 yields:

\[ S = 0.5 \times 10^\{\left(0.078P-6\right) - \left(0.35 + 0.05P\right) \times (SN) \times \log \frac{\text{CBR}_1}{\text{CBR}_0}\} \]  

(4-7)

The deterioration caused by the passage of a vehicle depends on the weight and physical configuration of the wheels and axles of the vehicle. In order to obtain a manageable measure of the capacity for damage, the concept of equivalent axle load, \( P \), is used. This is a common technique of pavement design. Each axle loading that actually passes over the road is converted to the equivalent number of 18,000 pound single axle loadings that would cause the same amount of damage. Using this method, the total traffic loading can be represented as a single number of equivalent single axle loads. The variable \( V \) used in the deterioration equation 4-1 represents the number of equivalent 18,000 pound single axle loads using the surface during the year.

The model computes \( V \) as a function of the number and
type of vehicles using the road. This information is specified by the model user based on traffic predictions. The computation of $V$ can be represented as follows:

$$V = \sum_{i=1}^{n} b_i V_i$$  \hspace{1cm} (4-8)

when $b_i$ represents the number of type $i$ vehicles using the road during the year being analyzed. $V_i$ is the weighting factor to convert one type $i$ vehicle to the number of 18,000 pound single axle loads that would cause the same pavement damage. The present model can handle up to seven basic vehicle types. $V_i$ is found by the equation (38):

$$V_i = [SA_i x 10^{(0.1 WS_i - 1.8)}] + [TA_i x 10^{(0.07 WT_i - 2.2)}]$$  \hspace{1cm} (4-9)

where:

$SA_i$ = number of single axles on type $i$ vehicles

$TA_i$ = number of tandem axles on type $i$ vehicles

$WS_i$ = weight in Kips of the single axles on type $i$ vehicle

$WT_i$ = weight in Kips of the tandem axles on type $i$ vehicle

The model has now been discussed to the point where uncorrected annual deterioration can be computed as a function of the input variables that define pavement design, traffic, and subsoil. Most of the relationships presented were developed from regression analysis of AASHO Road Test data. The AASHO test was an accelerated test that lasted
approximately two years. As a result of the short test time, it is likely that very little of the deterioration observed was a result of time dependent variables. However, there is ample evidence that time is a factor in the deterioration of asphalt pavements. Aging of asphalt mixtures has been well documented (41, 42). Swelling and shrinking of subsoil also often plays an important role in the performance of the pavement. In some instances this movement of the underlying soil overshadows traffic damage as a cause of deterioration (40). To simulate time dependent deterioration the uncorrected annual deterioration, ΔPSI, found by equation 4-1 is modified by adding an annual deterioration factor. Since there is little information on the function governing time dependent deterioration, a constant factor is used to represent this damage.

\[ ΔPSI' = ΔPSI + AGE \]  

(4-10)

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

Another adjustment built into the model allows
deterioration rate to increase with age. Uncorrected
deterioration, $\Delta PSI$, determined by equation 4-1 is a linear
function of equivalent axle loads, $V$. However, plots of
serviceability as a function of axle loads often indicate an
increasing rate of deterioration during service life. To
simulate this type of deterioration function, the annual
deterioration prediction can be modified as follows:

$$\Delta PSI' = \Delta PSI \times (1 + J)^{AG}$$  \hspace{1cm} (4-11)

where $AG$ is the age of the pavement in years and $J$ is the
factor which can be adjusted to correspond to local experi-
ence. A value for $J$ in the range of .03 to .05 appears to
simulate the increase in rate with load application found on
some sections of the AASHO road test. If experience indi-
cates that serviceability is a linear function of load
application, $J$ should be set equal to zero to eliminate the
effect of this adjustment mechanism.

Substituting equation 4-1 and 4-10 into equation 4-11
yields:

$$\Delta PSI = (KxSxV + ACE) \times (1 + J)^{AG}$$  \hspace{1cm} (4-12)

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

$$PSI_1 = PSI_0 - \Delta PSI'$$  \hspace{1cm} (4-13)
where PSI\textsubscript{0} is the serviceability at the start of the year and PSI\textsubscript{1} represents serviceability after deterioration but before any maintenance work is done.

Serviceability was developed as a subjective measure of the pavement's ability to serve traffic. It is difficult to directly relate serviceability to maintenance action. Fortunately, during the AASHO Road Test, serviceability was correlated with measurable indicators of deterioration which can be related to maintenance. It was found that the serviceability of flexible pavements could be determined by the equation:

\[
\text{PSI} = 5.03 - 1.91 \log(1+\text{SV}) - 0.01\sqrt{\text{C+P}} - 1.38\overline{\text{RD}}^2 \tag{4-14}
\]

where; \overline{\text{SV}} is the mean slope variance in the wheel paths, (C+P) is a measure of the area of cracking and patching, and \overline{\text{RD}} is the mean rut depth. These were the measurable indicators of deterioration that were found to have the most effect on serviceability during the road test (32). Equation 4-14 was used during the road test to predict PSI as a function of \overline{\text{SV}}, (C+P) and \overline{\text{RD}}. Its use within the present maintenance model will be discussed in Section 4.4.5.

In order to relate the new PSI, predicted by equation 4-13, to maintenance action, a method is needed to estimate the physical deterioration (\overline{\text{SV}}, (C+P) and \overline{\text{RD}}) associated with that PSI. Reasonable estimates of these physical measures of deterioration are crucial to the operation of
the model.

Although the AASHO Road Test developed the regression equation to predict PSI from the measurement of $\overline{SV}$, $(C+P)$ and $\overline{RD}$, no attempt was made to find the reverse correlations. The data collected during the test and used to find equation 4-14 was, however, recorded in the published report (32).

These data were used to investigate the practicality of predicting $\overline{SV}$, $(C+P)$ and $\overline{RD}$ as a function of PSI. Polynomial regression analysis was used to determine the relationships between the variables and the statistical validity of the relationships that were found. This work is discussed in Appendix G. The regression analyses produced the following equations used in the model to predict the degree of physical deterioration as functions of PSI.

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

$$\overline{RD} = -0.031 \text{ PSI}^2 + 0.091 \text{ PSI} + 0.32$$

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

Values of $\overline{SV}$, $(C+P)$ and $\overline{RD}$ are estimated as functions of predicted PSI both at the start of each year of the analysis period and after the annual deterioration has been predicted. Estimates of maintenance work for the year are then based on these values.
4.4.2 **Maintenance Work Required**

The simulated maintenance actions of sealing and patching are based on the difference in \((C+P)\) before and after deterioration, i.e., the cracking that occurs during the year. Rut filling is based on the present rut depth with no filling being done until mean rut depth exceeds a specified depth.

To illustrate how the model simulates the operation of maintenance as a function of deterioration and specified maintenance policy, the equations governing the operations of sealing and patching will be described. The square meters of new \((C+P)\) for the road section, \(NA\), are estimated by:

\[
NA = [(C+P)_1 - (C+P)_0] \times WOS \times LOS \quad (4-18)
\]

where \(NA\) is the square meters of new cracking on the road section, and \((C+P)_0\) and \((C+P)_1\) are the estimated square of \((C+P)\) per 1000 square meters of surface for before and after deterioration respectively. \(WOS\) is the width of surface in meters, and \(LOS\) is length of section in kilometers.

The maintenance policies for sealing and patching are specified as the fractions of new cracking that will be sealed or patched. The square meters of sealing and patching are estimated by:

\[
SMS = FTS \times NA \quad (4-19)
\]

\[
SMP = FTP \times NA \quad (4-20)
\]
where FTS and FTP are the fractions of NA to be sealed and patched respectively. These are specified as part of the maintenance policy.

4.4.3 Quantities of Labor, Equipment and Material Required

To transform the quantities of maintenance required (in this case square meters of sealing and patching) to quantities of labor, equipment and materials is fundamentally a problem in engineering estimation. This part of the model and the corresponding parts for other maintenance operations may be thought of as automated estimating procedures. Productivity and consumption rates used in the following equations were determined partly by a review of existing maintenance studies of operational efficiency, and partly from the performance characteristics of the equipment involved. The assumptions underlying the detailed design of this model, including the productivity and consumption rates, and their sources are given in Appendix D.

Hours of labor or equipment time required to accomplish the quantity of work estimated in section 4.4.2 are determined by functions similar to the following equation, for the equipment hours needed to place patching material.

\[
EHN_{ij} = \frac{CCM_{ij} \times DOP \times SMP}{PT_2 \times 100} \quad (4-21)
\]

In equation 4-21, \( EHN_{ij} \) represents the hours of \( j \) type equipment needed to accomplish \( i \) type maintenance operation for
the year. \( \text{CCM}_{ij} \) is the hours of \( j \) type equipment needed to accomplish one unit of the \( i \) maintenance operation (in this case, one cubic meter of patching material), \( \text{DOP} \) is the average depth of patch placed in centimeters, \( \text{SMP} \) represents the square meters of patching as determined by equation (4-20), and \( \text{PT}_2 \) is an efficiency factor representing hours actually worked for each hour on the job. This factor can be used to calibrate the model for the efficiency of the maintenance organization involved. Each type of labor and equipment is estimated by an equation similar to equation 4-21.

Estimating the quantity of materials required is a straightforward process. Materials estimated are fuel for the maintenance equipment and the actual materials placed on the road during maintenance.

The quantity of fuel required for each type of equipment is estimated from the hours of equipment use previously estimated:

\[
\text{MP}_{ij} = \text{EHN}_{ij} \times C_{ij}
\]

(4-22)

where \( \text{MP}_{ij} \) represents liters of gasoline required for the \( j \) type of equipment to accomplish the \( i \) operation; \( \text{EHN}_{ij} \) is determined in equation 4-21 and \( C_{ij} \) is the appropriate fuel consumption factor.

It is also relatively simple to estimate the quantity of material placed on the road during maintenance. To continue with the example of sealing and patching, the tons of
bituminous patching material needed is found by:

\[
MBA_i = \frac{DCG \times DOP \times SMP}{100}
\]  

(4-23)

where DCG is the compacted density of the finished patch, and the other variables have been previously defined.

4.4.4 Monetary Cost

After the quantities of labor, equipment, and materials needed for the year have been determined, cost for each quantity is found. The quantities of each item are multiplied by the appropriate unit costs, which are furnished by the model user and may be either market prices or shadow prices as discussed in Section 3.2.3.3.

The estimated maintenance costs are subtotaled for labor, equipment and material. Each of these subtotals is then discounted to present worth values by equation 3-6.

The subtotals of present worth cost are then added to find the total, present worth cost for the year. The actual costs are also totaled for each year. These total yearly maintenance costs are accumulated as the model works to the end of the analysis period. The totals then become the totals of actual and present worth maintenance costs for use in the economic analysis along with construction and user costs.
4.4.5 Surface Improvement by Maintenance

After the maintenance work to be done during the year is determined (section 4.4.2) the resulting improvement in roadway condition can be estimated by reversing the order of calculations used to estimate the effects of deterioration. The changes in the physical measures of $\overline{SV}$, $\overline{RD}$, and $(C+P)$ are first estimated. These are then used to predict a new level of serviceability.

For the sealing and patching example, the improvements in $(C+P)$ and $\overline{SV}$ as a result of maintenance are estimated by:

\[
NA' = 0.5 \times \frac{SMS}{WOS}, \quad \text{and} \quad (4-24)
\]

\[
\Delta \overline{SV}' = 0.3 \times FTP \times \overline{SV} \times KK \quad (4-25)
\]

where:

- $NA'$ = square meters of $(C+P)$ eliminated by sealing,
- $SMS$ = area sealed in square meters
- $WOS$ = width of pavement surface,
- $\Delta \overline{SV}'$ = reduction in slope variance by patching,
- $FTP$ = fraction of new cracking, $NA$, that is patched,
- $KK$ = factor which varies between 0.0 and 0.1 as a function of $(C+P)$. The more $(C+P)$, the greater effect patching is expected to have on $\overline{SV}$.

Equations 4-24 and 4-25 are based on estimates of the physical effect the maintenance operation has on $(C+P)$ and $\overline{SV}$. These seem to be reasonably represented by the relation-
ships involved, however, additional research is needed to validate these equations.

The degrees of \((C+P)\), \(\overline{SV}\), and \(\overline{RD}\) after maintenance are determined by:

\[
\begin{align*}
(C+P)_2 &= (C+P)_1 - NA' \quad (4-26) \\
\overline{SV}_2 &= \overline{SV}_1 - \Delta SV' \quad (4-27) \\
\overline{RD}_2 &= \overline{RD}_1 - \Delta RD' \quad (4-28)
\end{align*}
\]

where the subscripts 1 and 2 represent the physical states of the surface before and after maintenance respectively.

The serviceability after maintenance, \(\text{PSI}_2\), can then be estimated by substituting the values of \((C+P)_2\), \(\overline{SV}_2\) and \(\overline{RD}_2\) into equation 4-14. This completes the estimate for serviceability variation for one year and results in simulation of behavior similar to that shown in Figure 4-3.

The maintenance model also estimates the roughness and coefficient of friction for each year of the analysis period. These variables are not used in the computation of maintenance cost but are required for proper operation of the road user cost model developed concurrently with this model.

Roughness, in inches per mile, is estimated as a function of serviceability as follows (28):

\[
RUF = \frac{5.0 - \frac{(\text{PSI}_0 + \text{PSI}_1 + \text{PSI}_2)}{3.0}}{0.015} \quad (4-29)
\]
Coefficient of friction is predicted as a function of surface age and varies linearly from 0.6 to 0.3 for wet pavement the first ten years of service, then remains 0.3 until resurfacing or the end of the analysis period (35). The coefficient of friction of dry pavement does not vary enough to be of interest to this study and is assumed to have a constant value of 0.7 (35).

This completes the description of the pavement maintenance subroutine. Similar subroutines estimate maintenance cost for the various operations shown in Figure 4.2 to complete the maintenance model.
CHAPTER V
MODEL CALIBRATION AND SENSITIVITY ANALYSIS

As described in Chapter IV, the maintenance model was designed by dividing the over-all cycle of deterioration and repair into the individual relationships involved. Functions were then selected to simulate these relationships as accurately as possible, based on the available information and various estimating techniques. These individual functions were then combined, within the model framework to produce the completed model. The choice of the individual functions and their combination determine the fundamental validity of the model. These functions are discussed and supported in Chapter IV and Appendix D.

To further assure that the model simulation was as accurately as possible, the model was calibrated by comparing its behavior with information, from other sources, concerning the behavior of actual roadways.

In a strict sense, a model can never be proven correct. However, it can be compared with information from other sources to see if inconsistencies occur which indicate that it is incorrect. Ideally this comparison should include a relatively long period of model use and field observation on a variety of projects. Although this type of long term field observation is beyond the scope of this study, the calibration done during the study on the basis of existing information helped assure that the model's
estimates were realistic.

In addition to comparing the model behavior with information from other sources, sensitivity tests of the model were made to identify the relationships which are most important to the accuracy of the model. The variation of estimates as the several functions are altered can be used to obtain a rough idea of the accuracy of the model. The variations also indicate the areas where any further study should be concentrated.

5.1 CALIBRATION

The model was calibrated with two types of information:

a. Records of maintenance cost and roadway condition and,

b. Other methods of predicting maintenance cost and roadway condition.

Not all the calibration work done on the model is discussed. Much of this work was done during model development in an informal manner. Comparisons were made against average values of maintenance cost and road condition and known trends of these values. It would be tedious to recount these early steps in the development of the model. However, some of the comparisons made late in the process of model development are presented to give an idea both of the probable accuracy, and of the difficulty of exactly determining that accuracy.
5.1.1 Maintenance Costs

Recorded maintenance costs are the most obvious type of information to compare with estimates made by the model. However, maintenance cost records are kept only in aggregated form. These are usually given by classes of road with no way to identify individual road sections or even average traffic on the class of road in question. Several attempts have been made to collect useful maintenance data from existing records but the results have been disappointing (3, 10, 54). For example, Oglesby and Altenhofen (10) report average annual maintenance costs per mile in the U.S. ranging from $50 to $690 for earth surfaces; $150 to $1,406 for gravel surfaces; and $250 to $1,373 for bituminous surfaces. There is little information available to explain these variations. Betz (3) collected information from 14 states and found variations between average statewide costs of $386 to $1,005 for gravel and $642 to $2,648 for bituminous surface treatment. Betz found the average annual maintenance cost of the states in his study to be $800 per mile for gravel surfaces and $1,200 per mile for bituminous surfaces. Although the use of this type of cost data is limited, it does give an idea of the range and magnitude of average maintenance costs that may be expected in the U.S. An early step in calibration was to insure that the model's estimates were in this general range for typical U.S. conditions of traffic, environment, design,
and maintenance policy.

Since detailed maintenance cost records were not available, estimates made by the model were compared to maintenance costs estimated by other predictive models. As discussed in Chapter II, these models were all developed to predict costs in a specific geographical area. Most predict maintenance cost as a function of road type and traffic volume. Very little information is available on the accuracy of these models but it is presumed that their estimates at least approximate local maintenance costs. Simple, linear type maintenance models based on local experience have been developed for many African countries (55). Several models for predicting gravel road maintenance cost are listed in Table 5-1.

The estimated maintenance cost of gravel roads as a function of traffic is plotted for several of these models in Figure 5-1. As with the average maintenance costs, there is little available information to explain the difference in these estimates.

To compare the results of these models with estimates made by the present maintenance model, a series of runs were made at two levels of maintenance policy and five levels of traffic. These runs were made for typical conditions of design, environment, and costs found in central Africa. The detailed description of input variables used to define the
Table 5-1: Existing Maintenance Models for Gravel Roads  
(Reference Number 55)

<table>
<thead>
<tr>
<th>Numbers in Figure 5-1</th>
<th>Models for Estimating Annual Maintenance Cost (MC)</th>
<th>Area of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MC = 406 + 10.6 ADT</td>
<td>Africa</td>
</tr>
<tr>
<td>2</td>
<td>MC = 140 + 5.6 ADT</td>
<td>Africa</td>
</tr>
<tr>
<td>3</td>
<td>MC = 420 + 2.8 ADT</td>
<td>Northern Nigeria</td>
</tr>
<tr>
<td>4</td>
<td>MC = 144 + 5.6 ADT</td>
<td>Nigeria</td>
</tr>
<tr>
<td>5</td>
<td>MC = 480 + 10.4 ADT</td>
<td>Niger</td>
</tr>
<tr>
<td>6</td>
<td>MC = 320 + 16.0 ADT</td>
<td>Chad</td>
</tr>
<tr>
<td>7</td>
<td>MC = 255 + 6.9 ADT</td>
<td>Togo</td>
</tr>
<tr>
<td>8</td>
<td>MC = 596 + 8.3 ADT</td>
<td>Tanzania</td>
</tr>
<tr>
<td>9</td>
<td>MC = 596 + 11.0 ADT</td>
<td>Tanzania</td>
</tr>
<tr>
<td>10</td>
<td>MC = 280 + 8.8 ADT</td>
<td>Zambia</td>
</tr>
<tr>
<td>11</td>
<td>MC = 227 + 4.0 ADT</td>
<td>Swaziland</td>
</tr>
<tr>
<td>12</td>
<td>MC = 142 + 5.6 ADT</td>
<td>Dahomey Land</td>
</tr>
</tbody>
</table>
Figure 5-1: Maintenance Cost for Gravel Roads as Predicted by Various Models
The annual maintenance costs estimated by the model during this series of runs are given in Table 5-2.

<table>
<thead>
<tr>
<th>Blading Frequency (Bladings/10,000 eq. veh.)</th>
<th>Average Daily Traffic</th>
<th>Annual Maintenance Cost ($ per mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>840</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1,340</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>1,800</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>760</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>1,000</td>
</tr>
</tbody>
</table>

Table 5-2: Estimated Maintenance Cost for Gravel Roads

These maintenance costs are plotted in Figure 5-2 along with the upper and lower limits of the estimates produced by the models in Table 5-1. This indicates that the estimates of the maintenance model are in general agreement with the estimates of the local models. The difference in estimated maintenance costs for the two blading frequencies also points
Figure 5-2: Estimates of Maintenance Cost per Mile vs. Average Daily Traffic for Gravel Roads
out the difficulty of a more direct comparison with an individual local model. The blading policy and possibly several other aspects of local practice must be known before such a comparison can be made. At present this information is not available.

Maintenance models have also been developed to estimate the maintenance cost of bituminous surface-treated roads in various localities. Four of these are listed in Table 5-3. These models have been adjusted for inflation by assuming a 5 percent annual inflation rate since the models were developed.

<table>
<thead>
<tr>
<th>Numbers in Figure 5-3</th>
<th>Models for Estimating Annual Maintenance Cost (MC)</th>
<th>Locality for Which Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$MC = 140 + 5.6 \text{ ADT}$</td>
<td>British West Africa (3)</td>
</tr>
<tr>
<td>2</td>
<td>$MC = 530 + 0.8 (\text{ADT-1,000})$</td>
<td>Niger (3)</td>
</tr>
<tr>
<td>3</td>
<td>$MC = 530 + 2.3 \text{ ADT}$</td>
<td>U.S. (54)</td>
</tr>
<tr>
<td>4</td>
<td>$MC = \begin{cases} 420 \text{ at 100 ADT} \ 1,150 \text{ at 400 ADT} \end{cases}$</td>
<td>U.S. (10)</td>
</tr>
</tbody>
</table>

Table 5-3: Existing Maintenance Models for Bituminous Surface Treated Roads

The annual maintenance costs predicted by these models are plotted as a function of traffic volume in Figure 5-3. In order to compare these to maintenance cost estimates made
Figure 5-3: Estimated Maintenance Costs For Bituminous Surface Treated Roads as Predicted by Various Models
by the present model, a series of runs were made for a project surfaced with bituminous surface treatment. Runs were made at three traffic volumes using both typical African and typical American unit costs. Detailed description of the factors used for each of these situations are given in Appendix H. The annual maintenance costs estimated during these runs are given in Table 5-4.

<table>
<thead>
<tr>
<th>Location of Simulated Project</th>
<th>Average Daily Traffic</th>
<th>Annual Maintenance Cost ($/mi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Africa</td>
<td>50</td>
<td>560</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>1,040</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1,600</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>845</td>
</tr>
<tr>
<td>United States</td>
<td>250</td>
<td>1,570</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>2,410</td>
</tr>
</tbody>
</table>

Table 5-4: Estimated Maintenance Cost per Mile of Surface-Treated Road

These estimated maintenance costs are plotted in Figure 5-4 along with the upper and lower bounds of the maintenance cost estimated by the local models. As in the case for gravel surfaces, the annual maintenance costs estimated for surface-treated roads falls within the range predicted by the local models.

Although the estimates based on U.S. cost data appear to be high, they are lower than the estimates of one of the
Figure 5-4: Estimates of Maintenance Cost per Mile vs. Average Daily Traffic for Bituminous Surface Treated Roads.
African models where labor rates are only a fraction of U.S. rates. This further illustrates the limitations of comparing model estimates at this level of detail. The prime value of this type of comparison is to compare the overall response of the model to that observed in other models, and in this respect the model behavior seems to be reasonable. To prepare the model for use in a specific area, more detailed information on environment, maintenance practices, productivities and unit costs should be used to make a more realistic calibration.

5.1.2 Roadway Condition

Both the estimate of maintenance cost and the estimate of road user cost depend on the predicted roadway condition during the analyses period. The estimates of roadway condition were also examined and compared to information from other sources, as discussed below, to assure that the predictions were as realistic as possible.

The model's predictions of paved surface conditions were compared to predictions based on conventional pavement design methods. These empirical methods are widely accepted for selecting the types and thicknesses of pavement layers. The conventional bituminous pavement design methods used in engineering practice can be represented by:
where $SN$ is the measure of pavement strength as defined by equation 3-6. However, these methods can also be used to solve for the total traffic load which is usually expressed as the accumulated total of equivalent axle loads that have been on the pavement:

$$\text{Total number of Equivalent Axle Loads} = f \begin{bmatrix} SN \\ \text{Minimum acceptable pavement condition} \\ \text{Environmental conditions} \end{bmatrix}$$

The present maintenance model can also be used to predict the number of equivalent axle loads it takes to reduce a given pavement to a minimum acceptable condition, when operating in a specified environment. The predictions of the model can then be compared to predictions made by the pavement design methods. This is a way to check the model's simulation of pavement behavior with methods based on a substantial body of experience.

Using the Burundi project data described in Appendix H, simulation runs were made on two pavement designs. The number of equivalent 18,000 pound axle loads before the surface deteriorated to a PSI level of 2.0 were noted.* The

*A PSI of 2.0 represents a surface condition found to be unacceptable by American drivers (32).
number of axle loads to reduce PSI to 2.0 was then found by the AASHO pavement design method for flexible pavements (56). The number of axle loads to "first major resurfacing" was found by the Asphalt Institute's pavement design method (38). The Asphalt Institute does not define the condition of the surface at which resurfacing should take place, however, in normal practice this is usually done when the existing surface deteriorates to a PSI level between 1.5 and 2.5. It can be assumed that this range of terminal condition was used in the development of the Institute's design method. The results of the comparison of the model predictions to predictions by these two design methods is given in Table 5-5.

<table>
<thead>
<tr>
<th>Structural Number of Pavement</th>
<th>Thousands of 18,000 Pound Axle Loads to Reduce Surface Condition to PSI = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AASHO Design Method</td>
</tr>
<tr>
<td>1.73</td>
<td>80</td>
</tr>
<tr>
<td>2.14</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 5-5: Axle Loads to Failure as Predicted by the Model and Two Pavement Design Methods

The estimates of the maintenance model are within the general range predicted by the two pavement design methods. Again this does not prove that the maintenance model can accurately predict future pavement behavior. However, it
indicates that the simulation compares reasonably with other work in the area.

Comparison of the number of axle loads to failure predicted by the model and the two pavement design methods is a comparison at only one point in the life of the pavement. This comparison gives no information about pavement behavior before failure. To get an idea of how the model's simulation of surface deterioration compares with recorded data, the results from a typical run, and the recorded behavior of three sections of the AASHO Road Test are plotted in Figure 5-5. All four pavements represented in Figure 5-5 have a structural number between 1.73 and 1.78.

Several aspects of pavement behavior are illustrated in Figure 5-5. The slopes of the PSI vs. axle load curves of the three road test sections increase with an increasing number of loads. This was typical, but not universal behavior of the road test sections. The slope obtained during the simulated run also increases with increasing number of loads although the improvement caused by maintenance, and represented by the vertical jogs, tends to offset this.*

The simulated improvements resulting from maintenance increase as the overall deterioration progresses. This

* Pavement maintenance on the AASHO Road Test was held to a minimum until after the pavement had deteriorated to a low PSI level and thus had little effect on pavement performance (32).
corresponds to the increasing amounts of maintenance effort being expended as the pavement deteriorates. This also corresponds to actual practice where maintenance done early in a pavement's life is less likely to increase serviceability than maintenance done later when overall performance may be improved by eliminating some of the major defects.

Although no numerical comparisons can be made on this information, the simulated behavior plotted in Figure 5-5 appears to reasonably represent various aspects of actual pavement behavior.

Another estimate of roadway condition made by the model is roughness of gravel surfaces. This is estimated as a function of blading frequency and traffic load. No direct information could be found against which to check these estimates. However, estimated roughness for a range of blading frequencies were compared to the range of roughnesses found by field measurement at two locations. The results of this comparison are shown in Table 5-6.

If the model predicts roughness realistically, the range of blading frequencies in these two locations should be between one and ten bladings per 10,000 equivalent vehicles with an average of approximately three per 10,000. No information is available on the actual frequencies used in the sampled areas. However, these frequencies are in the range that might be expected, based on the information available (10, 26, 43).
Figure 5-5: PSI vs. Applications of 18 kip Equivalent Axle Loads
Sensitivity analysis is used to identify which functions and input variables are important to the overall accuracy of the model. There are varying degrees of uncertainty in the functions and input variables used in the model and it is important to know which of these are most likely to affect the accuracy of the predictions made by the model. If these are identified, efforts to improve the simulation can be concentrated where they will have the greatest effect.

The sensitivity of the model to changes in these functions and variables is not constant for all situations but depends to some extent on the project being analyzed. For
example, if unit costs for labor are low, causing labor to be only a small fraction of the maintenance cost, the estimates are likely to be relatively insensitive to fractional changes in unit labor cost or labor productivity. However, if labor costs are extremely high and make up a large fraction of total maintenance cost, fractional changes in unit labor cost or productivity functions will have a greater effect on the model's estimates. The sensitivity analyses presented here are based on the St. Lucia project described in Appendix H. For another set of conditions, the sensitivity of the model to the various functions and variables will be different from the ones found here.

5.2.1 Sensitivity of Maintenance Cost

The results of simulation runs were analyzed to determine which components of maintenance cost were contributing significantly to the total maintenance cost. The results of this analysis for a gravel road simulation are given in Table 5-7. The relative contribution of each component to total maintenance cost indicates which factor prices and productivities should be examined most carefully.

For the gravel road in Table 5-7, labor and equipment account for 83 percent of the total cost. This indicates that the general productivity of the maintenance unit has a major effect on the total maintenance cost. The productivity of the maintenance unit is simulated within the model by
<table>
<thead>
<tr>
<th>Resource Consumed (minor items omitted)</th>
<th>Percentage of Total Maintenance Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor (Total)</td>
<td>45</td>
</tr>
<tr>
<td>Common Labor</td>
<td>16</td>
</tr>
<tr>
<td>Truck Driver</td>
<td>8</td>
</tr>
<tr>
<td>Equipment Operator (total)</td>
<td>14</td>
</tr>
<tr>
<td>Motorgrader</td>
<td>10</td>
</tr>
<tr>
<td>Equipment (Total)</td>
<td>38</td>
</tr>
<tr>
<td>Motorgrader</td>
<td>24</td>
</tr>
<tr>
<td>Dump Truck</td>
<td>5</td>
</tr>
<tr>
<td>Material (Total)</td>
<td>17</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>6</td>
</tr>
<tr>
<td>Gasoline (Dump Truck)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5-7: Breakdown of Maintenance Cost for Gravel Road in St. Lucia

specifying the percent of total paid working time the men and equipment are actually working. Since this productivity can vary widely between maintenance units, this function should be selected to represent the local maintenance unit as closely as possible.

Within the general category of labor and equipment, motorgrader time accounts for 24 percent. When operator and fuel are added, cost of motorgrader operation is 40 percent of the
total maintenance cost. Since this is by far the largest single maintenance cost, all functions that affect the simulation of motorgrader operation should be carefully determined. The percentage of time actually worked, speed of blading, width of coverage, and number of passes needed are all functions in the model which could cause substantial error. The economic cost per hour charged for the motorgrader should also be determined as realistically as possible.

The breakdown in Table 5-7 indicates that functions affecting truck operation should also be selected with care since trucks, drivers and fuel account for approximately 23 percent of the maintenance cost. The biggest cost of truck operation, for the unit costs specified, is gasoline. Therefore, factors affecting fuel consumption are important. Cost of common labor makes up 16 percent of the total and is thus also a significant contributor to the total maintenance cost. Other resources used for maintenance are not likely to seriously affect the accuracy of the estimated maintenance cost (for the specified conditions) unless their estimated quantities are in error by large percentages.

The breakdown of maintenance costs estimated by the model for a paved road is given in Table 5-8.

The cost breakdown in Table 5-8 indicates that labor and equipment accounts for only 40 percent of the total instead of the 83 percent found for the gravel road. Thus, although
<table>
<thead>
<tr>
<th>Resource Consumed (minor items omitted)</th>
<th>Percentage of Total Maintenance Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor (Total)</td>
<td>29</td>
</tr>
<tr>
<td>Common Labor</td>
<td>10.0</td>
</tr>
<tr>
<td>Truck Driver</td>
<td>5.0</td>
</tr>
<tr>
<td>Equipment Operators</td>
<td>2.8</td>
</tr>
<tr>
<td>Equipment (Total)</td>
<td>11</td>
</tr>
<tr>
<td>Motorgrader</td>
<td>5.4</td>
</tr>
<tr>
<td>Dump Truck</td>
<td>4.2</td>
</tr>
<tr>
<td>Material (Total)</td>
<td>60</td>
</tr>
<tr>
<td>Liquid Asphalt</td>
<td>2.6</td>
</tr>
<tr>
<td>Patching Mixture</td>
<td>46</td>
</tr>
<tr>
<td>Gasoline</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 5-8: Breakdown of Maintenance Cost for Paved Road in St. Lucia

the overall productivity of the maintenance unit is important it is not quite as crucial as for the gravel road simulation. Cost of bituminous-aggregate patching mixture is 46 percent of the total maintenance cost. The factors which affect the quantity of patching material used should have first priority on any effort to improve the accuracy of this simulation.
5.2.2 Sensitivity of Road User Cost

The roadway conditions predicted by the maintenance model often affects the predictions of road user cost. The sensitivity of road user cost predictions to the road condition predicted by the maintenance model, is examined in this section.

Roadway surface roughness is the measure of surface condition that most often has a significant effect on road user costs. This is especially true for unpaved roads which are usually rougher than paved surfaces. In the maintenance model, the roughness of unpaved roads is estimated as a function of blading frequency and traffic volume. The functions used for this estimate are not supported by direct research and their accuracy is uncertain.

To examine the sensitivity of the predicted road user costs to variations in the functions for estimating roughness of unpaved roads, a series of runs was made in which the functions are arbitrarily varied for each run. A base run was made with the normal functions used in the model to predict roughness. This was then adjusted to produce roughness predictions of 50 percent higher and 50 percent lower than the normal roughness. This range of roughness was selected to simulate major variations in the function now used. The maintenance and road user costs estimated during these runs are given in Table 5-9.
The estimates given are for one year of gravel road operation at approximately 115 vehicles per day, of which approximately 23 percent are heavy trucks.

<table>
<thead>
<tr>
<th>Roughness Predicted</th>
<th>Maintenance Cost</th>
<th>Adjusted Road User Cost*</th>
<th>Percent Change in User Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Prediction</td>
<td>291</td>
<td>3310</td>
<td>---</td>
</tr>
<tr>
<td>Roughness x 1.5</td>
<td>291</td>
<td>4290</td>
<td>+29</td>
</tr>
<tr>
<td>Roughness x 0.5</td>
<td>291</td>
<td>2920</td>
<td>-12</td>
</tr>
</tbody>
</table>

Table 5-9: Variation of Predicted Road User Cost with Variation in Roughness Prediction for Gravel Road. (Costs are in dollars per kilometer for one year)

Since the blading frequency was held constant for the three runs, there was no change in the predicted maintenance cost. Increasing the roughness estimate by 50 percent caused a 29 percent increase in road user costs. Decreasing the roughness estimate by 50 percent decreased road user costs by 12 percent. Although there is not always as much difference in the relative magnitudes of maintenance and road user cost as shown in Table 5-9, it can easily be seen that the functions which predict surface roughness may have a greater influence on the accuracy of the total transportation cost.

*Road user cost is adjusted by subtracting the change in willingness to pay from the estimated cost. See Section 3.2.2.
than any of the functions that affect maintenance cost. In this example, a 10 percent variation in user cost is greater than a 100 percent variation in maintenance cost. This indicates that for gravel roads, further study to improve the accuracy of the maintenance model should be concentrated on the functions that affect the estimate of surface condition.

In the simulation of paved roads, the estimates of both road user cost and maintenance cost are dependent on the prediction of surface condition. The sensitivity of these cost estimates to variations in the simulated deterioration rate of a paved surface were examined. A series of runs were made in which the deterioration rate was set both higher and lower than the rate selected for use in the model. To simulate a faster and a slower deterioration rate the variable AGE (see Section 4.4.1) was varied by multiplying by factors from 0.8 to 1.4. The results of these runs are given in Table 5-10. The costs shown are the present values of the costs accumulated over the 20 year analysis period. Traffic during these runs varied from 120 vehicles per day during the first year to 280 vehicles per day during the twentieth year. Approximately 20 percent of the vehicles were heavy trucks.

The results of these runs show that the prediction of maintenance cost for paved surfaces is sensitive to variations in the estimated rate of deterioration. Even for the modest variation of 20 percent from the rate being used in
Table 5-10: Variation of Predicted Maintenance and Road User Costs with Variations in the Deterioration Rate of Paved Roads (Costs are in $1000's per Kilometer)

In the current model, the maintenance cost prediction varies either 22 or 31 percent depending on the direction of variation. For larger variations the effect on estimated maintenance cost becomes more pronounced; a 40 percent increase in deterioration rate causes a 72 percent increase in maintenance cost for the project being simulated.

Variations in deterioration rate also affect the estimates of road user cost but these changes are not as pronounced as the changes in estimated maintenance costs. For the runs listed in Table 5-10, a 40 percent increase in deterioration rate increased road user costs only 2.2 percent. This is much different from the case for gravel roads where estimated road user costs were found to be very sensitive to
the prediction of surface roughness (see Table 5-9).

The reason for this difference in sensitivity is that gravel roads are normally much rougher than paved roads and the roughness is likely to limit vehicle speed. At this level, changes in roughness change the trip times required with corresponding variations in the cost for driver, passenger, vehicle, and cargo time. Since paved roads are normally much smoother than gravel roads, roughness is less likely to limit vehicle speeds than the alignment and grade of the roadway. If the roughness is the limiting factor it is likely to be less severe than is often the case on gravel roads.

Although estimated user cost was not found to be particularly sensitive to variations in the deterioration rate for the runs examined, the change in the sum of maintenance and road user cost is significant. Because of the difficulties of determining the deterioration rate a variation of 40 percent is not out of the question. For this magnitude of increase in the rate, the combined maintenance and user cost increased 7.9 percent. Thus, not only does the deterioration rate have a major influence on maintenance cost but it may also significantly affect the total cost of transportation.
CHAPTER VI
APPLICATIONS OF MODEL

This chapter will illustrate how the model can be used to make decisions concerning the design, construction and maintenance of highway systems. The objective of this thesis is to provide techniques for answering the first two basic questions relating to highway maintenance:

a. What is the best balance between initial system cost and future maintenance cost, and
b. What degree or level of maintenance should be provided on existing roads.

The example problems in this chapter indicate that the maintenance model, used integrally with the rest of the total cost model, is useful for analyzing these types of questions. The examples given do not represent all the possible uses of the model but are given to illustrate the application of the model to a few questions of interest.

The examples in this chapter use present worth of total cost for a 20 year analysis period as the criteria for judging competing strategies. Use of the model with more complex evaluation methods is illustrated in Chapter VII.

The examples given in this chapter are based on a two lane road in Burundi, Africa with the design characteristics and within the environment described in Appendix H. The unit costs used for labor equipment, and material are typical for
central Africa and are listed in Table H-1. The discount rate used for the present worth calculation is 8 percent.

More detailed information is given within the individual sections where it is appropriate to more fully describe the strategies being simulated.

6.1 SELECTION OF PAVEMENT DESIGN

There is a large body of literature concerned with the problems of pavement design (39, 56). Most of this research has been directed toward finding the required depth and type of pavement required to withstand the effects of predicted future traffic for a given design period. The design period is usually fixed. Twenty years is a common design period in U.S. practice. In usual practice, the possible benefits of a longer or shorter design period are not considered. Although the type of pavement design selected effects the future road user and maintenance costs, the designer normally has no satisfactory method to analytically consider these costs during design of the pavement.

The use of this model, with its simulation of the system for an analysis period, allows the questions of length of design period and effect on road user and maintenance costs to be explored.

To illustrate this use, a series of simulation runs were made for the project described above. Four typical pavement design strategies were tried. Pavement maintenance policy
was the same for all pavements. The traffic demand function specified for this project resulted in traffic varying from 60 to between 140 and 160 vehicles per day over the 20 year analysis period.* Twenty percent of the total vehicles are heavy trucks. The results of the simulation runs are given in Table 6-1.

<table>
<thead>
<tr>
<th>Structural Number of Pavement</th>
<th>Construction Cost</th>
<th>Maintenance Cost</th>
<th>Adjusted Road User Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.13</td>
<td>16.2</td>
<td>7.5</td>
<td>22.2</td>
<td>45.9</td>
</tr>
<tr>
<td>1.25</td>
<td>18.4</td>
<td>3.3</td>
<td>21.8</td>
<td>43.5</td>
</tr>
<tr>
<td>1.44</td>
<td>20.0</td>
<td>2.7</td>
<td>21.8</td>
<td>44.5</td>
</tr>
<tr>
<td>1.78</td>
<td>22.0</td>
<td>2.1</td>
<td>21.4</td>
<td>45.5</td>
</tr>
</tbody>
</table>

Table 6-1: Present Worth of Costs for Various Pavement Designs (in $1000's/km.)

Of the designs examined, the pavement with a structural number of 1.25 results in the lowest total cost. Variations in the proposed pavement designs resulted in substantial changes in both the estimated costs for maintenance and the costs to the road users. As mentioned, conventional pavement design methods do not consider maintenance and road user costs. At best, the designer can make only crude estimates

*The difference in traffic growth is a result of the price elasticity of demand and the difference in road user costs between the various surfaces.
of these future costs.

This example illustrates how use of the present model makes it possible to consider these maintenance and road user costs along with construction costs at the design stage.

6.2 DETERMINING BLADING POLICY FOR GRAVEL SURFACES

Surface maintenance is by far the most costly type of maintenance operation for most gravel roads. Maintaining the surface usually consumes over half, and sometimes practically all, of the maintenance cost. Typically, most of this cost of surface maintenance is needed for periodic blading or dragging of the road to prevent or remove corrugations and move gravel back toward the center of the road.

As a result, the cost of maintaining a gravel road will be heavily affected by how often it is bladed. The frequency of blading also affects the level of service provided by the road and thus the cost to the road user. These two relationships result in a tradeoff between maintenance cost and user cost.

To illustrate how this tradeoff can be explored by use of the model, a series of runs were made in which blading frequency was varied and the resultant present worth of the cost for a 20 year analysis period observed. The road used in this example starts with a gravel surface 15 centimeters deep. Traffic varies from 50 vehicles per day during the first year to between 115 and 135 vehicles for the twentieth
year. Ten percent of the total vehicles are medium trucks. All input variables except blading frequency are held constant for the series. Results of the runs are given in Table 6-2.

<table>
<thead>
<tr>
<th>Blading Frequency (eq. veh./blading)</th>
<th>Construction Cost</th>
<th>Maintenance Cost</th>
<th>Adjusted Road User Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>13.7</td>
<td>4.4</td>
<td>18.4</td>
<td>36.5</td>
</tr>
<tr>
<td>2,000</td>
<td>13.7</td>
<td>3.2</td>
<td>18.4</td>
<td>35.3</td>
</tr>
<tr>
<td>3,500</td>
<td>13.7</td>
<td>2.1</td>
<td>20.6</td>
<td>36.4</td>
</tr>
<tr>
<td>12,000</td>
<td>13.7</td>
<td>1.4</td>
<td>33.7</td>
<td>48.8</td>
</tr>
</tbody>
</table>

Table 6-2: Present Worth of Costs for a Gravel Road and Various Blading Frequencies (in $1000's/km.)

The construction cost is the same for all runs and therefore is not needed to find the blading frequency that gives the lowest cost.

The maintenance strategy of blading once every 2,000 vehicles resulted in the lowest total cost. Additional runs with blading policies somewhere between 2,000 vehicles per blading and the two adjacent policies could be tried in order to more accurately locate the policy of minimum total cost. However, it appears that total transportation cost is relatively insensitive to frequency of blading in the range between 1,000 and 3,500 vehicles per blading. For this situation, it is probably not within the accuracy of the model to
locate, more exactly, the frequency of lowest cost.

It should be noted that the results shown are based on a particular combination of roadway design, traffic volume, unit prices and discount rate for capital and may not be valid for other situations.

Although this example specifically examines the frequency of blading gravel roads, the model can be used in a similar fashion to evaluate alternative maintenance policies involving other maintenance operations simulated by the model.

6.3 SELECTION OF MAINTENANCE POLICY FOR PAVED ROAD

There are two parts to the problem of selecting the maintenance policy for a paved road. First, the mix of operations to be performed must be selected. It is usually possible to repair a given type of deterioration in more than one way. However, the methods available are not likely to be equally effective or equally costly. Second, the level of maintenance to be provided must be determined. As discussed earlier, selection of this level involves tradeoffs between maintenance cost, user costs and reconstruction costs. This is the type of problem illustrated in Section 6.2 for gravel road maintenance.

Both the mix of operations and the level of effort which make up maintenance policy are usually determined by the judgement and experience of the maintenance supervisor involved. The maintenance supervisors who make these decisions
normally have no way of obtaining the information needed to systematically analyze this problem.

This section illustrates how the present model can be used to investigate the problem of selecting a maintenance policy in an analytical manner. The example examines alternative methods of maintaining a bituminous paved surface. Both mixes of operations and level of maintenance effort are investigated.

A series of runs were made for a bituminous pavement with a structural number of 1.78. Each run simulated the behavior of the system for a 20 year analysis period in which traffic varied from 120 vehicles per day during the first year to 280 vehicles per day during the twentieth year. Approximately 20 percent of these vehicles were heavy trucks.

The tradeoff examined between different maintenance operations involves repair of pavement cracking by two methods. The cracks that appear in any year can either be sealed with liquid asphalt and a cover aggregate or a thin patch can be placed over the cracked area. In practice a combination of these methods is often used. Minor cracking may be sealed while more severe cracking may be patched. In the model, either or both of these two methods may be specified by selecting the percent of new cracking to be repaired by each method. The maintenance policies specified for the series of runs are given in Table 6-3. The resulting estimates of
maintenance and road use costs made by the model are also listed. Since the construction cost is the same for each of the individual simulations this estimate is not included. The PSI levels at the end of the 20 year analysis period are also listed.

<table>
<thead>
<tr>
<th>Maintenance Policy</th>
<th>PSI at end of analysis period</th>
<th>Maintenance Cost</th>
<th>Adj. Road User Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Seal</td>
<td>% Patch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.0</td>
<td>.0</td>
<td>*</td>
<td>0</td>
<td>48.8</td>
</tr>
<tr>
<td>.5</td>
<td>.1</td>
<td>1.8</td>
<td>3.2</td>
<td>36.2</td>
</tr>
<tr>
<td>.9</td>
<td>.0</td>
<td>1.0</td>
<td>2.7</td>
<td>36.5</td>
</tr>
<tr>
<td>.0</td>
<td>.9</td>
<td>2.8</td>
<td>5.0</td>
<td>34.6</td>
</tr>
<tr>
<td>.9</td>
<td>.7</td>
<td>2.6</td>
<td>5.3</td>
<td>34.8</td>
</tr>
</tbody>
</table>

*Det eriorated to PSI = 1.0 at year 13

Table 6-3: Present Worth of Costs for a Paved Road with Various Maintenance Policies (in $1000's/km.)

Based on the results of the runs listed in Table 6-3 a number of observations can be made about the effect of the maintenance policies on the costs and pavement conditions of the example project.

When neither sealing nor patching is specified, the surface deteriorates much faster and reaches a PSI level of
1.0 in 13 years. The roughness of the surface during this run caused the estimated road user costs to increase. In normal practice this surface would be resurfaced before the end of the 20 year period. Resurfacing was not specified for this run to simplify the example, however, for a more complete analysis another run should be made with resurfacing specified to examine the consequences of this strategy.

At the other extreme, when very heavy maintenance is specified the roadway remains in good condition throughout the analysis period. A maintenance policy of patching 0.9 of all new cracking each year results in a PSI of 2.8 at the end of the period. A still more costly maintenance policy which specifies patching 0.7 and sealing 0.9 of all new cracking resulted in a 2.6 PSI for the twentieth year. However both of these policies result in very high maintenance costs and rather high total costs.

The two maintenance policies between the extremes produce the lowest estimated total costs. The policy that specifies sealing 0.9 of new cracking has the lowest estimated total cost. However the policy that specifies sealing 0.5 and patching 0.1 of new cracking is estimated to cost only slightly more and this policy maintains the road surface at a higher level. Either of these policies appear to be

---

*The area of sealing and patching may be greater than the area of cracking because the area surrounding a cracked area, but not actually cracked yet, may also be sealed or patched as preventative maintenance.
superior to the extreme policies of very light or very heavy maintenance.

These runs illustrate how the model may be used to examine the consequences, both in terms of costs and service-abilities provided, for a series of alternative maintenance policies.

The examples described in this chapter illustrate a few of the tradeoffs that can be examined with the aid of the model. These examples have illustrated that decisions normally made only on the basis of personal judgement can be examined in a systematic way by using the cost and roadway condition estimates made by the model.
Chapter VI discussed how the model developed during the study can be used to help evaluate alternative highway strategies. The examples given were evaluated on the basis of minimum total cost as measured by total present worth cost. If properly applied, this is a valid measure of economic performance. However, decisions on public investment should often consider other important aspects of the problem not measured by economic performance. Two such aspects are: (a.) constraints that limit the range of strategies which may be considered, and (b.) the differences in risk of alternative strategies.

A variety of concepts and techniques have been developed to help the decision maker properly consider these, and other factors, not included in monetary cost. However, application of these techniques requires the prediction of future system behavior in more detail than is usually available for highway systems.

The model developed during this study provides the predictions needed to apply some of these techniques. This chapter illustrates the use of the present model in conjunction with some of these aids to decision making.

The techniques chosen for these examples were developed within the general concepts of maintainability and decision theory and are presented in the two following sections.
7.1 APPLICATION OF MAINTAINABILITY

The concept of maintainability and most of the existing techniques based on this concept were developed in the electronics and aerospace fields. The systems developed in these fields, like highway systems, often require high operating and maintenance costs.

As the electronics and aerospace systems became more complex the problem of keeping these systems in operation became increasingly difficult. Problems with equipment failure and high maintenance cost became intolerable (57,58). This led to gradual change in the design philosophy.

The dominate objective of design had been to achieve high levels of performance when the system was functioning properly. This changed and in addition to concern about potential performance level, more emphasis was placed on questions relating to how often the system was going to function properly and how much effort would be required to keep it functioning.

Since the systems in question were complex, it was not usually apparent what effect various design options would have on behavior during service life. To answer these questions a variety of systematic methods were developed to assist the designer. Some of these methods are based on the concept of maintainability.
Maintainability is a built in characteristic of the physical system (57). It can be defined as a measure of the effort needed to maintain the system. In actual application, maintainability is defined more specifically in ways to be most compatible with the analysis being made (59).

The concept of maintainability provides a means of quantifying the expected future maintenance of a system; and allows consideration of this maintenance at the design stage along with the more familiar design parameters of performance, reliability, and initial cost.

Maintainability can be used as a design parameter in two ways; (a.) to allow tradeoff between future maintenance requirements and other design parameters in order to find the "optimum" design, or (b.) to specify a maximum acceptable maintenance effort that the system may require. The total maintenance costs for the life of the system, as used earlier in this thesis, can be considered a measure of maintainability. These costs (reduced to present value) have been used in the tradeoff analysis given in Chapter V to find the "optimum" design of lowest total present worth cost. Thus the use of maintainability in tradeoff analysis has already been illustrated for highways.

The other use of maintainability as a means of specifying the maximum acceptable amount of maintenance may also be useful for highways. This is now done in the electronics and aerospace fields where the required
maintainability is routinely specified by the Department of Defense and the National Aeronautics and Space Administration.

Constraints on the available highway maintenance may prevent the implementation of the lowest cost strategy if that strategy calls for more maintenance than will actually be performed. If a strategy requires heavy maintenance that is not provided, premature failure of the road and/or high user costs may result. This in turn may cause the actual total cost to be higher than for alternative strategies that required no more than the available maintenance. To avoid this type of situation any future constraints on maintenance should be considered at the design stage. Limitations or constraints on the amount or type of maintenance that will be available are real problems in highway design. These constraints may stem from a variety of causes. Future maintenance budgets may be limited for administrative or political reasons; the maintenance organization may not be capable of performing certain types of operations for lack of equipment, materials or training; or there may be an administrative or political decision to make low maintenance a goal in itself. Use of the present model permits these types of limitations to be specified and allowed for during design of the road.
7.1.1 Use of Maintainability as a Design Constraint

The following example will illustrate how a limitation on the future maintenance available to a system can be specified as a system requirement and how this may lead to improved decision making.

The example problem is the selection of a strategy for providing low volume highway transportation between two specified points. Traffic demand, shadow prices for labor, equipment, and material, environmental conditions, and other factors needed to define the problem are known.

The strategy is to be selected on the basis of low total present worth cost, subject to a minimum maintainability specification.

Based on knowledge of the local government and its maintenance organization, it is unrealistic to expect that roads in the area will receive more maintenance than can be provided by $2,000 per kilometer (present worth value) for the analysis period. An arbitrary definition of maintainability, $M$, for use on low cost roads is:

$$ M = \frac{10^6}{MC} \quad (7-1) $$

where $MC$ is the present worth value of the expected maintenance for the analysis period. Therefore, a minimum $M$ of 50 is specified to stay within the expected maintenance constraint.
The total cost model is used to find the average costs of providing transportation at this location by a variety of strategies. As a result of this series of runs the following four strategies were selected as the most promising.

<table>
<thead>
<tr>
<th>No.</th>
<th>Strategy</th>
<th>Const.</th>
<th>Maint.</th>
<th>User</th>
<th>Total</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gravel (2,000 veh/blading)</td>
<td>13.7</td>
<td>3.2</td>
<td>18.3</td>
<td>35.2</td>
<td>31</td>
</tr>
<tr>
<td>B</td>
<td>Gravel (6,000 veh/blading)</td>
<td>13.7</td>
<td>1.7</td>
<td>28.2</td>
<td>43.6</td>
<td>59</td>
</tr>
<tr>
<td>C</td>
<td>Surface Treatment (+2 seal coats)</td>
<td>21.4</td>
<td>1.8</td>
<td>14.1</td>
<td>37.3</td>
<td>55</td>
</tr>
<tr>
<td>D</td>
<td>Bituminous Concrete (2&quot;)</td>
<td>27.4</td>
<td>1.1</td>
<td>12.7</td>
<td>39.1</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 7-1: Present Worth Costs for Various Designs (in $1000's/kilometer)

Strategy A which specifies a well maintained gravel surface is eliminated from consideration since its expected M is less than the specified minimum. Of the remaining three strategies, C, which specifies a bituminous surface treatment plus two additional seal coats during the analysis period, results in the lowest total present worth cost. Although the expected maintainability of this strategy is above the specified minimum, it is very close to the limit. The degree of uncertainty in selecting the minimum required maintainability and in the accuracy of the model should be considered in the decision. If these estimates involve a
high degree of uncertainty, as is likely, strategy D, which has a much higher maintainability, may be the best choice.

If the strategy for this project had been selected on the basis of minimum total cost, with no consideration given to the limit on future maintenance, strategy A would have been selected. The limit on available maintenance would have resulted in a maintenance policy similar to that of strategy B. Actual user costs would also have been similar to those of strategy B, and the total costs of providing the system would have been greater than for either strategies C or D.

This example illustrates how an anticipated constraint on future maintenance can be analytically specified as a design constraint by using the concept of maintainability, and how this can lead to a better decision.

7.2 APPLICATION OF DECISION THEORY

Although the model is deterministic and deals only with average values of the variables involved, it is recognized that these are actually random variables. The uncertain nature of the predicted costs should be considered in the decision process. Statistical decision theory is a method of incorporating this uncertainty into the analysis (60). Adding to the problem of decision making under uncertainty is the usual aversion of most people to risk. In general, people do not consider the value of a dollar constant for
all conditions of risk (61).

For example a person may be willing to accept a gamble that offers a .5 probability of winning $10 and a .5 probability of breaking even.

\[
\begin{align*}
\text{.5} & \quad \text{$10$} \quad 10 \times .5 = 5 \\
\text{.5} & \quad 0 \quad 0 \times .5 = 0 \\
\text{Expected Value} & = 5
\end{align*}
\]

and at the same time reject a gamble that offers a .9 probability of winning $10 and a .1 probability of losing $30 although the expected value of the second gamble exceeds that of the first.

\[
\begin{align*}
\text{.9} & \quad \text{$10$} \quad 10 \times .9 = 9 \\
\text{.1} & \quad \text{$-30$} \quad -30 \times .1 = -3 \\
\text{Expected Value} & = 6
\end{align*}
\]

This type of choice has been found to be the predominate behavior of people in situations involving risk (62). Aversion to risk is not an idle concept but exerts a strong influence on decisions concerning public investment. A conservative but relatively costly design goes unnoticed by
the public. A less conservative design that promises to reduce costs but includes a small chance of early failure is noticed by the public only if the early failure occurs. This phenomenon tends to make public officials even more adverse to risk.

The concept of utility theory was developed to quantify preferences in choices involving uncertainty (63). Utility theory can be combined with expected cost decision analysis to incorporate aversion to risk into the decision process.

7.2.1 Decision Theory Based on Expected Costs

The following example problem will select a strategy on the basis of minimum expected total cost by applying simple decision theory. Neither maintainability constraints nor risk aversion will be considered in this example.

A series of simulation runs identifies two strategies that are predicted to give low total costs:

Gravel Surface (2,000 veh/blading) -$29,300/km.

Surface Treatment (+2 seal costs) -$31,000/km.

However, the growth of the traffic demand function is very uncertain. Since this could have a major effect on the predicted costs, additional runs are made using demand functions which represented the possible range of traffic growth. Four demand functions and the associated probability that each might represent the actual demand are predicted based on
forecasts of economic growth for the area. These demand functions and their probabilities define the probability mass function for demand. The total present worth cost is predicted for each demand function and multiplied by its associated probability to find the expected total cost for each strategy.

$$
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Surface Type} & \text{Demand Function} & \text{Traffic (ADT)} & \text{Probability} & \text{Total Cost} & \text{Expected Costs} \\
\hline
\text{Gravel} & 1 & 50-250 & 0.1 & 59.0 & = 5.9 \\
& 2 & 50-150 & 0.2 & 37.2 & = 7.4 \\
& 3 & 50-100 & 0.35 & 28.8 & = 10.1 \\
& 4 & 50-50 & 0.35 & 23.5 & = 8.2 \\
\hline
\text{Total Expected Cost (Gravel)} & & & & = 31.5 \\
\hline
\text{Surface Treatment} & 1 & 50-250 & 0.1 & 45.0 & = 4.5 \\
& 2 & 50-150 & 0.2 & 35.0 & = 7.0 \\
& 3 & 50-100 & 0.35 & 30.0 & = 10.5 \\
& 4 & 50-50 & 0.35 & 26.5 & = 9.2 \\
\hline
\text{Total Expected Cost (Paved)} & & & & = 31.2 \\
\hline
\end{array}
$$

Table 7-2: Expected Present Worth Cost Calculations for Two Strategies Using Probability Mass Function of Demand
The strategy using a gravel surface promised to be the lowest cost solution based on average demand function. However, when the more detailed, probability mass function of demand is used to find expected cost the strategy using a surface treatment produces a slightly lower cost. The difference in the total costs of the two strategies is small, but the change in results from the average value method is substantial.

7.2.2 Decision Theory Based on Utility

The simple, decision analysis shown in the preceding section is useful for reducing uncertain outcomes to manageable size. The many possible outcomes and the probability that each will occur is reduced to the single measure of expected cost for each strategy. However, this implies that the decision maker is not adverse to risk. Since few people, firms or governments are indifferent to risk, the concept of utility has been developed to account for the decision makers' aversion to risk. In essence, utility theory provides a surrogate measure of preference which includes both the expected monetary outcome and the risks involved. This measure can be used in place of monetary units for making decisions and these decisions will then include consideration of the decision maker's aversion to risk.

The utility function of a hypothetical decision maker for use on the problem in Section 7.2.1, might be of the
form shown in Figure 7-1. The numbers along the X axis represent the possible range of total costs for the project. The numbers on the Y axis represent the \( \pi \) probability of winning, and \((1-\pi)\) probability of losing an imaginary lottery where winning results in a total cost of $20,000 for the project and loosing results in a total cost of $80,000.

For example the Y coordinate of point B defines a lottery with a 1.0 probability (certainty) of $20,000. This agrees with the X coordinate of point B which also indicates a certain cost of $20,000. At point A (origin) the Y coordinate defines a lottery with a 1.0 \((1-\pi)\) probability of $80,000 which again agrees with the certain cost of the X coordinate. The dotted line between points A and B is the locus of points whose X coordinate equals the expected values of the lotteries defined by the Y coordinates.

The curve shown in Figure 7-1 is a plot of the decision maker's indifference between the probabilities (on the Y axis) of winning the lottery and the certain project costs shown on the X axis. For instance, the decision maker would just as soon choose a strategy for the project that is certain to cost $43,500 as choose a strategy that has a .8 probability of costing $20,000 and a .2 probability of costing $80,000. Since the second strategy has an expected cost of $32,000 \((8 \times 20,000 + .2 \times 80,000)\) this
Figure 7-1: Utility Curve For Example Problem
curve indicates that the decision maker is willing to spend up to $11,500 of the public's money over the expected cost to avoid the risk involved in the second strategy.

The decision maker must determine the shape of his utility function for the problem involved. Raiffa (60) describes one method of doing this by determining the decision maker's preference for a series of simple lotteries. Once this function has been determined, lotteries defined by values of \(\pi\) can be substituted for the total costs used in the expected cost computation in Section 7.2.1. The results of these computations are shown in Table 7-3.

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Demand Function</th>
<th>Total Cost $1,000/km.</th>
<th>Utility of Total Cost</th>
<th>Probability</th>
<th>Expected Utilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>1</td>
<td>59.0</td>
<td>.58</td>
<td>.1</td>
<td>.06</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>37.2</td>
<td>.87</td>
<td>.2</td>
<td>.17</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>28.8</td>
<td>.94</td>
<td>.35</td>
<td>.33</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>23.5</td>
<td>.98</td>
<td>.35</td>
<td>.34</td>
</tr>
<tr>
<td></td>
<td><strong>Total Expected Utility (Gravel) = .90</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Treatment</td>
<td>1</td>
<td>45.0</td>
<td>.78</td>
<td>.1</td>
<td>.08</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>35.0</td>
<td>.89</td>
<td>.2</td>
<td>.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30.0</td>
<td>.93</td>
<td>.35</td>
<td>.33</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>26.5</td>
<td>.96</td>
<td>.35</td>
<td>.34</td>
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<tr>
<td><strong>Total Expected Utility (Surface Treatment) = .93</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-3: Calculations for Decision Based on Expected Utilities.
The decision between surface treatment and gravel can now be made on the basis of maximum expected utility, allowing for the decision maker's aversion to risk. In this example the surface treated roadway has a higher expected utility than the gravel surface.

The expected cost analysis in Section 7.2.1 also found the surface treatment to be preferable but by only a small margin. To compare the results of the two methods, the total expected utilities are converted to certain project costs by using the utility curve in Figure 7-1. The results of the two decision methods discussed in this section along with the total costs based on the average demand curve are given in Table 7-4.

<table>
<thead>
<tr>
<th>Method of Analysis</th>
<th>Gravel</th>
<th>Surface Treatment</th>
<th>Difference (G-ST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Costs for Average Demand Function</td>
<td>29.3</td>
<td>31.0</td>
<td>-2.3</td>
</tr>
<tr>
<td>Total Expected Costs Using Probability Mass Function</td>
<td>31.5</td>
<td>31.2</td>
<td>+0.3</td>
</tr>
<tr>
<td>Total Expected Utilities Using Probability Mass Function</td>
<td>33.3</td>
<td>30.0</td>
<td>+3.3</td>
</tr>
</tbody>
</table>

Table 7-4: Results of Decision Analyses. (Total Present Worth Costs in $1,000's/km).
These results show substantial variation between methods. This variation implies that statistical decision theory is a worthwhile refinement in the decision process if uncertainty and aversion to risk are involved.
CHAPTER VIII
SUMMARY AND EVALUATION

8.1 SUMMARY

The objective of this study was to devise systematic and practical techniques to allow consideration of two fundamental questions of highway maintenance; (a) what is the best balance between initial system cost and future maintenance cost and, (b) how much maintenance should be done on existing systems.

In order to systematically consider future maintenance during design, and to select the best maintenance policy for existing roads, a method of estimating the future costs and effects of maintenance is required. The maintenance model developed during this study estimates these costs and effects as functions of traffic, environment, maintenance policy, and the physical characteristics of the system.

To use the maintenance model effectively, maintenance is considered as part of the larger problem of providing low cost transportation. An overall model framework was designed. The maintenance model operates within this larger framework where it contributes the simulation of roadway deterioration and repair to the simulation of the total system. Other submodels for estimating the construction and road user costs and the volume of traffic were designed by others as part of this larger study. These three submodels operate
within the total cost model to estimate the present worth of the total cost of providing transportation by a specific strategy. Using the model, alternative strategies for a project can be quickly and easily evaluated on the basis of present value of total transportation cost.

In designing the maintenance model the common approach of attempting to relate maintenance costs to combinations of the significant variables by using regression analysis was rejected. Instead, the physical cycle of deterioration and repair was simulated as realistically as possible, and maintenance cost and roadway condition were estimated on the basis of this simulation. The cycle of deterioration and repair was divided into the individual physical activities that make up the cycle. These activities were simulated individually and then combined within the maintenance model to simulate the total physical system.

The fundamental validity of the maintenance model rests on how accurately the individual relationships are simulated and how realistically they are combined within the model. However, to assure that the model's estimates are within reason, the model behavior was compared to information from a variety of sources as described in Chapter V. These comparisons indicated that the model predictions were in agreement with the available information.
Sensitivity analyses were made to determine the relative importance of the functions within the model, and the input variables used by the model, to the overall accuracy. These analyses indicated that the model estimates are quite sensitive to variations in the functions and input variables that affect roadway surface condition. The prediction of the deterioration rate for paved roads and the roughness of unpaved roads were found to have significant influence on the cost predictions.

The model's ability to examine several types of tradeoffs using the goal of minimum transportation cost was illustrated by example problems in Chapter VI.

Chapter VII suggests how the model may also be used to systematically consider factors other than cost minimization in the decision process. Simplified examples using the concepts of maintainability and decision theory are presented.

8.2 EVALUATION

As a result of the work done during this study and summarized in Section 8.1, some idea of the capabilities and limitations of the model was gained. These capabilities and limitations will be discussed in this section.

8.2.1 Structure of Model

The structure of the model appears to be conceptually sound. The model responds reasonably to variations in design
characteristics, traffic loads, and environmental descriptions. No major inconsistencies were encountered during the numerous runs made for calibration, sensitivity analysis, and example problems. The structure of the model, which bases the maintenance costs estimates on the overall simulation of roadway behavior, appears to be practical in estimating future maintenance costs. Most of the advantages of this model over other methods of estimating maintenance cost are made possible by the flexible structure of the model in which individual physical relationships are explicitly simulated. Some of these advantages are discussed in the following section.

8.2.2 Model Capability

The model can be used to address the two fundamental questions of highway maintenance which were the objectives of this study. Future maintenance cost can be considered as a design parameter along with the more usual parameters of construction and road user cost. Thus, the question of balance between initial cost and future cost can be systematically analyzed. The model can also be used to help determine the most desirable level of maintenance as was illustrated in Sections 6.2 and 6.3.

The ease and economy of making simulation runs and the level of detail of the model's estimates also make it possible to use the techniques of maintainability, statistical decision
theory and possibly other decision making techniques in selecting the construction-maintenance strategy. With these techniques, such factors as uncertainty, aversion to risk and various resource constraints can be incorporated into the design process. Since these are often important factors affecting highway decisions, a practical method of considering them quantitatively should lead to better design decisions.

Another advantage of the maintenance model over other available methods of estimating maintenance cost is its capability to be adjusted to a wide variety of local conditions. The type of model structure used in which the individual physical relationships are simulated, also allows the model's accuracy to be improved as new information is gained about the individual relationships. Thus new information from a variety of sources may be used to improve the model. In addition, sensitivity analysis can be used to identify which types of information are most important to the accuracy of the model. This information is essential to the design of an effective research program for model improvement.

8.2.3 Model Accuracy

The capabilities discussed in the last section and the model's immediate usefulness are dependent on the accuracy of the model. This accuracy is difficult to assess since there is no standard against which to compare model estimates.
However, the calibration runs and sensitivity analysis discussed in Chapter V and other work with the model during the course of the study, give a general idea of model accuracy.

Based on the work done during this study, the model appears to be accurate enough for use in the early planning stages of project development. The model is not sufficiently developed to be used as a production model. However, it could be carefully used by an analyst who understands the present limitations to make preliminary evaluations on a variety of proposed strategies.

The model could also be used for more detailed design work on selected projects. The model should be useful for exploring a wide range of strategies and selecting the ones that promise lowest transportation costs. However, the strategies suggested by the model should be used only if they satisfy other tests to insure a practical design.
CHAPTER IX
RECOMMENDATIONS FOR FUTURE WORK

Further attempts to refine the maintenance model on the basis of available data are not expected to be productive. More specific and detailed data than are now available are needed if accuracy is to be improved. Two types of studies are recommended to gather this data; formal research studies to improve the simulation of roadway surface deterioration, and application of the model to specific projects.

9.1 SURFACE DETERIORATION

Since the sensitivity analysis indicated that variations in the prediction of surface conditions have a greater influence on the predicted maintenance and road user costs than variations in any other part of the model, early research effort should be concentrated in this area. This is particularly true because some of the functions used to simulate surface deterioration were based on incomplete information.

Specific recommendations for further work in this area are as follows:

1. Attempt to verify the relationships between PSI and the physical measures of deterioration that affect maintenance demand. These are now based on the regression analyses done during this study and during the AASHO Road Test. However, the data from these
analyses were from a limited geographical area. Data from other locations should be collected to determine if the behavior found in the sampled area is typical of a bituminous pavement.

2. The effect of maintenance action on the physical measures of deterioration and on PSI should be measured for a variety of maintenance procedures. The study should be carried out over a period of several years so that the long term as well as the short term effects of maintenance can be observed.

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

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

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

6. The effect of surface condition on vehicle speed should also be studied. This information is not used directly in the maintenance model but is necessary if the effect of maintenance on road user cost is to be accurately determined. It should be possible to collect data on this relationship in conjunction with the studies suggested above. The vehicle speeds could be observed on sections of road that are alike in all respects except roughness. These observations could then be used to verify or adjust the functions in the user cost model that simulate the relationship between roughness and vehicle speed.

Other work could be suggested to improve model accuracy. However, the suggested studies are believed to offer the most benefit to the model for a given expenditure.
9.2 MODEL APPLICATION TO SPECIFIC PROBLEMS

Another recommendation for future work is that the model be adapted to a specific locality and used on one or more low volume road projects. To obtain the greatest model improvement from this work the following procedure is proposed.

1. The project or projects selected should be typical for the area of interest. Projects with unusual features such as landslide problems, unusual soil conditions, or extremely deep excavations should be avoided.
2. The input variables that define the project problem and the strategies to be tried should be determined as carefully as possible to match local conditions. All assumptions described in Appendix D should be examined and adjusted to match local practice and local experience.
3. Make trial simulation runs using typical designs and maintenance problems. These should be made as early in the study as practical so comparison with any local records, models or experience can determine any major inconsistencies.
4. Do preliminary sensitivity analysis for the local conditions, and unit prices to determine which areas of research promise the most improvement in model accuracy.
5. Research suggested by the preliminary sensitivity analysis that can be done quickly and easily should be
done and the appropriate model functions adjusted to
match the results of that research.

6. The model should be used to aid in selecting construc-
tion-maintenance strategies for the project or pro-
jects.

7. Observations of the actual maintenance costs and road-
way conditions should be compared to the costs and
conditions predicted by the model. This phase of the
study may require several years if the deterioration
of a paved surface is involved. However, most of
the other types of information needed for model re-
finement should be available within two or three years.

The procedure outlined should calibrate the model to the
specific area and make it possible to better evaluate the
practicality of the model for its intended use. It can then
be used with more confidence for other projects within the
area. This type of trial application should also result in
more general improvement to the model which will increase its
accuracy for use in other areas.

Use of the model on actual projects combined with more
specific research of the type suggested in section 9.1 should
result in continuing improvement.
REFERENCES


REFERENCES CONT.


REFERENCES CONT.


REFERENCES CONT.


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BIOGRAPHY OF THE AUTHOR

Born: Early Park, Indiana, February 9, 1933

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Andrew - September 16, 1963
Jonathan - January 1, 1967

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Massachusetts Institute of Technology - S.M. - 1968

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Ass't. Area Engineer - U.S. Bureau of Public Roads, 1962-1965

Highway Engineer (trainee) - U.S. Bureau of Public Roads, 1960-1962


Draftee - U.S. Army, 1956-1958

Highway Engineer - Alaska Road Commission, Summer 1956

Societies: American Society of Civil Engineers
Tau Beta Pi
Sigma Xi
Chi Epsilon

Licenses: Registered Professional Engineer in Indiana and Missouri
APPENDIX A
DEFINITION OF SYMBOLS USED IN TEXT

PSI  AASHO present serviceability index
TC'\_x  Present worth of the total cost for strategy x
CC\_xi  Construction cost predicted for year i using strategy x
MC\_xi  Maintenance cost predicted for year i using strategy x
UC\_xi  Road User cost for strategy year i using strategy x
d  Discount rate or opportunity cost of capital
\Delta CS\_ij  Change in consumer surplus when changing from strategy i to strategy j
\Delta WTP\_ij  Change in willingness to pay when changing from strategy i to strategy j
PWC  Present worth of cost
AC  Actual cost
YR  Year of analysis period in which costs are incurred
SV  Mean slope variance in wheel path
(C+P)  Square root of sq. m. of cracking and patching per 1000 sq. m.
RD  Mean rut depth in wheel paths
\Delta PSI  Uncorrected annual deterioration
K  Calibration factor for deterioration equation
V  Number of applications of an equivalent axle load
S  Slope of deterioration rate
P  Equivalent single axle load
α  Function of \( P \) defined by equation 4-3
β  Function of \( P \) defined by equation 4-4
\( \bar{SN'} \)  Effective structural number of pavement
\( \bar{SN} \)  Actual structural number of pavement
CBR  California bearing ratio
Di  Depths of pavement layers
\( a_i \)  Weighting factor for pavement layers
\( SA_i \)  Number of single axle on type \( i \) vehicle
\( WS_i \)  Weight in kips of the single axle on type \( i \) vehicle
\( WT_i \)  Weight in kips of the tandem axle on type \( i \) vehicle
AGE  Annual drop in PSI independent of traffic damage
AG  Time in years since construction or resurfacing of pavement
J  Adjustment factor to simulate an increasing deterioration rate with time for paved surfaces
\( PSI_0 \)  PSI at start of year
\( PSI_1 \)  PSI after deterioration and before maintenance
NA  Square meters of new \((C+P)\) for one year
WOS  Width of roadway surface
LOS  Length of road section
SMS  Square meters of sealing
SMP  Square meters of patching
FTS  Fraction of NA to be sealed per year
FTP  Fraction of NA to be patched per year
\( EHN_{ij} \)  Hours of \( j \) type equipment needed to accomplish \( i \) type maintenance operation for year
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CCM\textsubscript{ij}</td>
<td>Hours of i type equipment needed to accomplish one unit of the i maintenance operation</td>
</tr>
<tr>
<td>DOP</td>
<td>Average depth of patch in centimeters</td>
</tr>
<tr>
<td>PT\textsuperscript{2}</td>
<td>Hours actually worked for each hour on the job.</td>
</tr>
<tr>
<td>MP\textsubscript{ij}</td>
<td>Liters of gasoline required for the j type of equipment to accomplish i operation</td>
</tr>
<tr>
<td>C\textsubscript{ij}</td>
<td>Fuel consumption in liters per hour</td>
</tr>
<tr>
<td>MBA\textsubscript{i}</td>
<td>Tons of bitumenous patching material needed for operation i</td>
</tr>
<tr>
<td>DCG</td>
<td>Compacted density of patch</td>
</tr>
<tr>
<td>NA'</td>
<td>Square meters of (C+P) eliminated by sealing</td>
</tr>
<tr>
<td>Δ\textsubscript{SV}'</td>
<td>Reduction in slope variance by patching</td>
</tr>
<tr>
<td>KK</td>
<td>Adjustment factor that controls the effect that patching has on SV.</td>
</tr>
<tr>
<td>RUF</td>
<td>Roughness in inches per mile</td>
</tr>
<tr>
<td>M</td>
<td>Maintainability, ($10^6$/present worth of maintenance costs for analysis period)</td>
</tr>
<tr>
<td>π</td>
<td>Probability of winning an imaginary lottery used in decision analysis section</td>
</tr>
</tbody>
</table>
APPENDIX B

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APPENDIX D

ASSUMPTIONS AND DEFINITIONS

This appendix contains the basic assumptions and the definitions of the variables used in the maintenance model. The assumptions were made, as far as was practical, on the basis of information found during the review of literature. Where nothing could be found in the literature, relationships were estimated as realistically as possible by estimating, based on whatever elements of logic, experience, and judgement could be brought to bear. As a result of this effort the assumptions are believed to be realistic. However, if the model user has additional information available, as a result of either local experience or research done subsequent to this study, it can be used to upgrade the model by modifying the appropriate assumptions used in the model.

The contents of this appendix are listed on the following two pages.
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**Definition of Variables Used in Model**

Variables and Assumed Values Discussed in First Part of This Appendix

Variables that Define Resources Used for Maintenance

Miscellaneous Other Variables
ASSUMPTIONS USED IN THE GENERAL MAINTENANCE MODEL

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

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

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

4. Ratio of net working time to total working time for labor is 45 min/hr (PCL = 0.75).

ASSUMPTIONS FOR BITUMINOUS SURFACE MAINTENANCE

I. General

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

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

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

\[
PSI = 5.03 - 1.91 \log (1 + \overline{SV}) - 0.01 \sqrt{C + P} - 1.38 \overline{RD}^2
\]  (32)

where:

\( \overline{SV} \) = the mean slope variance in wheel paths
\( (C + P) \) = the area of surface that is either cracked or patched (expressed in \( m^2/1000m^2 \))
\( \overline{RD} \) = the mean rut depth in the wheel paths.

4. The coefficient of traction for wet pavement is initially .6 (IFRCW = .6). This decreases due to bleeding and aggregate polishing to a minimum of .3 (FFRCW = .3) in about ten years after construction or resurfacing (DFRC = .03)  (35)

5. A wet surface is assumed for that fraction of the year input as IMPS.

6. The coefficient of traction for dry pavement surface

* Numbers in parentheses refer to references
is constant and equal to 0.7 for the life of the surface (35).

7. Rolling resistance on paved surfaces is constant at 0.01 for all conditions and ages of interest (31).

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

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

This equation is based on the regression analysis described in Appendix G.

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

$$\text{Roughness} = (5.0 - \text{PSI})/0.15 \quad (36)$$

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

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

$$(C+P) = 0 \quad \text{if PSI}>4.3$$

This equation is based on the regression analysis described in Appendix G.

17. The mean rut depth ($\overline{RD}$) can be estimated for any level of serviceability by the relationship:

$$\overline{RD} = -0.031\text{PSI}^2 + 0.091\text{PSI} + 0.32$$

See Appendix G.

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

II. Assumptions Concerning Patching

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

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

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

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

5. Placing and rolling cold mix for deep patches or skin patches requires the following expenditure of labor and equipment per cubic meter (13,14,23):
   a) 7.0 hours of common labor  (CCM1 = 7.0)
   b) 3.0 hours of dump truck    (CCM2 = 3.0)

6. The cost of transporting cold mix from a source to the road section can be found using the same estimates of productivity and consumption used for transporting gravel.
7. The percent of liquid asphalt used in the cold mix is 6% of the aggregate weight (AC = 0.06)

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

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

where KK is an adjustment factor that varies between 0.0 and 1.0 with the amount of cracking that appears each year. That is, the more patching that is done, the more SV will be affected.

III. Assumptions Concerning Sealing

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

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

3. The costs of transporting the liquid asphalt are absorbed in the costs of the distributor and are not explicitly calculated.

4. Aggregate is applied at rate of 14 kilo/m². (SA=14)

5. Bitumen is applied at rate of 1.2 litres/m². (SB=1.2)
6. Sealing 100 square meters required the following expenditure of labor and equipment (13,14,23):
   a) 1.4 hours of common labor (CS1 = 1.4)
   b) 1.4 hours of truck (CS2 = 1.4)
   c) 0.4 hours of distributor (CS3 = 0.4)
   d) 0.3 hours of roller (CS4 = 0.3)

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

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

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

IV Assumptions Concerning Rut Repair

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

2. All costs for preparing and storing the premixed patching material are included in a "price for the material at the central location". The cost of obtaining the material on the road of interest is thus dependent only on this source "price" and the cost of transportation.
3. The cost of transporting cold mix from a source to the road section can be found using the same estimates of productivity and consumption used for transporting gravel.

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

5. The rut filling operation is assumed to be mechanical with a motorgrader spreading the material. Placing and compacting patching material for rut repair requires the following expenditures of labor and equipment per cubic meter \( (13,14,37) \):
   a) 1.0 hours of common labor \( (CRF1 = 1.0) \)
   b) 0.7 hours of dump truck \( (CRF2 = 0.25) \)
   c) 0.25 hours of motorgrader \( (CRF3 = 0.2) \)
   d) 0.2 hours of roller \( (CRF4 = 0.2) \)
   e) 0.2 hours of distributor \( (CRF5 = 0.2) \)

6. Since only the deeper ruts will be filled, the average rut depth will be reduced each time ruts are repaired.

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

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

8. Assume that the shape and size of the average rut filled will be as follows \( (32) \):
Note: This assumption should be valid for values of FRF between 10 and 30 percent.

Volume of patching material required for one kilometer of road-way (CMPR) = \( \frac{4 \times FRF \times 1.6 \text{ MRD} \times .8m \times 1000m}{100 \text{ cm/m}} \)

= \( 50 \times FRF \times RD \)

ASSUMPTIONS FOR GRAVEL ROAD MAINTENANCE

I. General

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

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

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

4. Gravel surface will retain its general characteristics until the thickness of the surface is less than 7 cm (TSC=7) (49). Then, if regravelling is not specified in the maintenance policy, it will revert to the characteristics of an earth surface until reconstructed.

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

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

7. One cubic meter of loose gravel weighs 1800 kilograms (DLG=1.8).

II. Assumptions Concerning Blading

1. The surface can be bladed with two passes/area of the grader over the area to be bladed (Pass 1 = 2) (46).

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

3. Except during dry season, traffic compacts the surface satisfactorily after blading and no additional compaction need be provided (46,64).

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

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

III. Assumptions Concerning Regravelling

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

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

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

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

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

6. Four grader passes per area are necessary for re-gravelling. (PASS2 = 4)

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

8. Assume that amount of gravel lost from surface is directly proportional to the total weight of vehicles using road. The number of each type of vehicle will be converted to an
equivalent number of 1600 kilogram vehicles. The total number of equivalent vehicles will be used to estimate gravel loss. This assumption appears to explain the difference in gravel loss between the two most complete reports concerning gravel loss (13,43).

9. Assume that 0.9 metric tons of gravel is lost per year per kilometer for each 365 equivalent vehicles (one per day) that uses the road. (GL = .9) (13,43,45).

ASSUMPTIONS FOR EARTH ROAD MAINTENANCE

I. General Assumptions

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

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

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

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

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

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

II. Assumptions Concerning Blading

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

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

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

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

ASSUMPTIONS FOR DRAINAGE MAINTENANCE

1. Basic measure of work is cubic meters of soil that is removed from ditches and drainage structures.

2. All work is done with a standard crew of 25 laborers, 4 trucks and one motorgrader. The assumed operation uses the motorgrader to grade the ditches to their original depth. The laborers load the spoil into trucks for removal and do whatever hand work is necessary to clean out and repair the drain-
age structures within the work area.

3. This crew is capable of removing 100 cubic meters of sediment from the drainage ditches in one day (6 hours working time and a ratio of working time to total time of 3:4 (PCL=.75) (5,13,23,65).

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

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

where:

- \( \text{RF} \) = annual rainfall in centimeters (27)
- \( \text{TF} \) = adjustment factor for terrain (13)
  - a. mountainous = 1.0
  - b. rolling = 2.0
  - c. flat = 3.0
- \( \text{SSF} \) = adjustment factor for side slopes = \((1/\text{cut slope}) + (1/\text{fill slope}) + (0.5)\) (27)

ASSUMPTIONS FOR MAINTENANCE OF BITUMINOUS SHOULDERS

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

2. The shoulders are sealed a minimum of once every ten years (0.1 of shoulder area is sealed each year) (23).
3. The most common repair needed will probably be filling the depressions that form the edge of the travelled surface. The repair needed for this deterioration is considered to be proportional to the patching and rut filling needed for the travelled surface since they are both affected by the traffic volume, subsoil quality, and climate (12).

4. The patching and rut filling needed for bituminous shoulders increases by 50% (SBI = .5) for each meter that the roadway surface is less than 7 meters (10). (i.e., A 6 meter wide road will require 50% more shoulder maintenance than one 7 meters and a 5 meter road will require 50% more than the 6 meter road.)

5. Bituminous shoulder for a 7 meter wide travelled surface require 10% as much patching and rut filling per area as the travelled surface (23).

ASSUMPTIONS FOR GRAVEL SHOULDER MAINTENANCE

1. Shoulder maintenance is a minor fraction of the total maintenance cost (13,3). Therefore, typical maintenance policy will be assumed instead of complicating the model by asking the model user to specify policy.

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

3. The shoulder are bladed an additional time for each 500 vehicles per day (ADT) above 500 ADT. (FREQF = 500) (12).

4. The number of needed shoulder bladings is greater for
narrow roadways. It is assumed that the need for bladings increases 50% (SGI = .5) for each meter that the roadway surface is less than 7 meters (13).

5. One shoulder blading requires 2 passes of the motor-grader (23) (4 passes for both shoulders). That is, the model assumes all shoulders are less than 2.5 meters wide.

6. Shoulder blading can be scheduled to be done when surface is damp and therefore no water need be added.

7. Bladed shoulder material must be rolled since it is not likely to be compacted by traffic (49).

8. Shoulder can be satisfactorily compacted with same number of passes as for compacting bladed gravel road (PR4) and the width which needs to be rolled is not wider than roller. Therefore, passes needed to roll one section of road (both shoulders) = 2 x PR4.

DETAILED ASSUMPTIONS OF EQUIPMENT PRODUCTIVITY AND CONSUMPTION

1. Motor Grader (3.7 meter blade)

Production

a. coverage = 2.4 meter/pass \( \text{PMG1} = 2.4 \)

b. ratio of net working time to total working time = 45 min/hr \( \text{PMG2} = 0.75 \)

c. working travel speed = 6 kilometer/hr \( \text{PMG3} = 6.0 \)
Consumption:

a. fuel consumption = 15 liter (diesel)/total hours \[CMG1 = 15.0\]
b. operator time = 1.0 hours/total work hours \[CMG2 = 1.0\]

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

Production

a. coverage = 2 meters \[PR1 = 2\]
b. ratio of net-to-total work time = 45 min/hr \[PR2 = .75\]
c. work travel speed = 6.0 kilometer/hr \[PR3 = 6.0\]
d. 3 passes will compact 6 cm of loose material \[PR4 = 3\]
e. 5 passes will compact 10 cm of loose material \[PR5 = 5\]

Consumption

a. fuel consumption = 5 liters (gasoline)/hr \[CR1 = 5\]
b. operator time = 1.0 hrs/total working hrs \[CR2 = 1.0\]

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

Production

a. capacity = 6.0 cubic meters \[PWT1 = 6.0\]
b. ratio of net-to-total work
time = 45 min/hr

c. average haul speed = 40 kilometer/hr

d. average spray speed = 10 kilometer/hr

e. loading and delay time = 20 min/round trip

f. width of sprayed area = 4 meters

g. passes needed to apply water = 2

Consumption

a. fuel consumption = 9 liters (gasoline)/total hrs

b. driver time = 1.0 hrs/total working time

4. Dump Truck (3 cubic meters)

Production

a. capacity = 3 cubic meters

b. ratio of net-to-total working time = 45 min/hr

c. haul speed = 40 kilometers/hr

d. time to load (during regravelling) = 5 min

e. time to unload (gravel) = 2 minutes
f. delay time per round trip
(regravelling = 5 minutes) \[PT_6 = 5\]

Consumption
a. fuel consumption = 7 liters (gasoline)/hr \[CT_1 = 7\]
b. driver time = 1.0 hrs/total working time \[CT_2 = 1.0\]

5. Loader (1 cubic meter capacity)

Production
a. production rate (regravelling operation) = 
\[30 \text{ M}^3 \text{ (10 trucks)} \text{ per hour/working time}\] \[PL_1 = 30\]
b. ratio of net-to-total working time = 
\[45 \text{ min/hr}\] \[PL_2 = 0.75\]

Consumption
a. fuel consumption = 12 liter gasoline/hr \[CL_1 = 12\]
b. operator time = 1.0 hrs/total work hours \[CL_2 = 1.0\]

6. Bituminous Distributor

Production
a. capacity = 5M³ \[PD_1 = 5\]
b. ratio of net to total working time = 
\[45 \text{ min/hr}\] \[PD_2 = 0.75\]
Consumption.

a. fuel consumption (gasoline) =
   7 liters/hr  \( CD_1 = 7 \)

b. driver time = 1.0 hours/total
   work hour  \( CD_2 = 1.0 \)

7. Tractor and Mower (1.8 meter mower)

Production

a. capacity = 1.8 meter per pass  \( PV_1 = 1.8 \)

b. ratio of net working time to
total working time = 45 min/hr  \( PV_2 = 0.75 \)

c. working travel speed = 5 kilometers/hour  \( PV_3 = 5.0 \)

Consumption

a. fuel consumption = 4 liters/kilometer  \( CV_1 = 4.0 \)

b. driver time = 1.0 hour/total work
   hour  \( CV_2 = 1.0 \)
# DEFINITION OF VARIABLES USED IN MODEL

Variables and Assumed Values Discussed in First Part of This Appendix

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<td>Depth of gravel that needs water added during dry season</td>
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<td>AG2</td>
<td>CM. of gravel added during re-gravelling</td>
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<td>CFDR</td>
<td>Coefficient of friction of dry paved road</td>
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<tr>
<td>CPRT</td>
<td>SQUARE ROOT of area of surface that is either cracked or patched ( \sqrt{\text{m}^2/1000\text{m}^2} )</td>
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<td>CRF1</td>
<td>Hours needed to place and compact 1 m(^3) of coldmix in ruts</td>
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<td>CS1</td>
<td>Hours of common labor needed to seal 100 m(^2)</td>
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<td>CS2</td>
<td>Hours of truck needed to seal 100 m(^2)</td>
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<td>Hours of distributor needed to seal 100 m(^2)</td>
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<td>CS4</td>
<td>Hours of roller needed to seal 100 m(^2)</td>
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<td>Density of compacted gravel</td>
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<td>Decrease in coefficient friction of wet pavement per year</td>
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<td>DLG</td>
<td>Density of loose gravel</td>
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<td>DOP</td>
<td>Average depth of patch</td>
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<td>Minimum coefficient of friction of wet pavement</td>
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<td>FIXSV</td>
<td>Reduction in slope variance due to maintenance</td>
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<td>FREQS</td>
<td>Vehicles/day for gravel shoulder blading</td>
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<td>GL</td>
<td>Metric tons gravel lost/year/equivalent Vehicle/day</td>
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<td>IPRCW</td>
<td>Coefficient of friction of wet new pavement</td>
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<td>Fraction of year an earth road is impassable</td>
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<td>MRD</td>
<td>Mean Rut Depth in wheel path</td>
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<td>PASS2</td>
<td>No. of motorgrader passes needed per area during regravelling</td>
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<td>PCL</td>
<td>Ratio of net working time to total working time for labor</td>
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<td>ROLL</td>
<td>Rolling resistance of paved road</td>
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<td>SA</td>
<td>Kg. of aggregate/m² of sealing</td>
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<td>SB</td>
<td>Liters of bitumen/m² of sealing</td>
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<td>SBI</td>
<td>% increase in paved shoulder maintenance required by each M of width less than 7M.</td>
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<td>ABOVE But for gravel shoulders</td>
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<td>SV</td>
<td>Mean slope variance in wheel paths</td>
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<td>TCRC</td>
<td>Depth at which regravelling occurs</td>
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</tr>
<tr>
<td>WA1</td>
<td>Percent water to be added for blading gravel roads in dry season</td>
<td>4</td>
</tr>
<tr>
<td>WA2</td>
<td>Percent water added to new gravel</td>
<td>4</td>
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</table>
Variables Associated with Pavement Condition

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CMPR</td>
<td>cubic meters of material used to fill ruts per kilometer</td>
</tr>
<tr>
<td>CPRTK</td>
<td>square root of cracking and patching (\sqrt{m^2/1000 \ \text{m}^2}) per kilometer at start of year</td>
</tr>
<tr>
<td>CPRTX</td>
<td>square root of cracked area (\sqrt{m^2/1000 \ \text{m}^2}) after maintenance</td>
</tr>
<tr>
<td>CPRT</td>
<td>square root of cracking after deterioration and before maintenance (\sqrt{m^2/1000 \ \text{m}^2}) per kilometer</td>
</tr>
<tr>
<td>DELCP</td>
<td>increase in cracking caused by traffic (square meters) per kilometer</td>
</tr>
<tr>
<td>DELRD</td>
<td>increase in rut depth caused by traffic (inches)</td>
</tr>
<tr>
<td>DELSV</td>
<td>increase in slope variance caused by traffic</td>
</tr>
<tr>
<td>FIXCP</td>
<td>improvement in cracking due to maintenance (square meters) per kilometer</td>
</tr>
<tr>
<td>FIXRD</td>
<td>improvement in rut depth due to maintenance (inches)</td>
</tr>
<tr>
<td>FIXSV</td>
<td>improvement in slope variance due to maintenance</td>
</tr>
<tr>
<td>MRDK</td>
<td>mean rut depth at start of year</td>
</tr>
<tr>
<td>MRDX</td>
<td>mean rut depth after maintenance (inches)</td>
</tr>
<tr>
<td>PSI</td>
<td>PSI at end of year</td>
</tr>
<tr>
<td>PSIK</td>
<td>PSI at start of year</td>
</tr>
<tr>
<td>RD</td>
<td>mean rut depth</td>
</tr>
<tr>
<td>SMP</td>
<td>area (square meters) patched per kilometer of road</td>
</tr>
<tr>
<td>Variables Associated with Pavement Condition</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>SMS</strong> - area (square meters) sealed per kilometer of road</td>
<td></td>
</tr>
<tr>
<td><strong>SV</strong> - mean slope variance (AASHO) after deterioration, before maintenance</td>
<td></td>
</tr>
<tr>
<td><strong>SVK</strong> - mean slope variance at start of year</td>
<td></td>
</tr>
<tr>
<td><strong>SVX</strong> - slope variance after maintenance</td>
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</tbody>
</table>
Variables that Define Resources Used for Maintenance

The following 13 variables are used for the quantities of labor, equipment and materials used for maintenance.

EHN - Number of equipment hours
LC - Hours of common labor
LEO - Hours of equipment operation
LF - Hours of foreman time
LG - Hours of greaser or helper time
LTD - Hours of truck driver time
MB - Liters of liquid asphalt
MBA - Metric tons of bituminous-aggregate patching mixture
MCA - Metric tons of crushed aggregate
MD - Liters of diesel fuel
MG - Metric tons of gravel
MP - Liters of gasoline
MW - Cubic meters of water

The above variables are used with a double subscript where the first number indicates the type of maintenance activity in which the resource was used as follows:

(1, ) - Blading earth or gravel surface (dry)
(2, ) - Regraveling
(3, ) - Vegetation Control
(4, ) - Drainage
(5, ) - Blading earth or gravel surface (damp)
(6, ) - Bituminous patching
(7, ) - Hauling bituminous patching
(8, ) - Sealing bituminous surface
(9, ) - Hauling materials for sealing
(10, ) - Filling ruts in bituminous surface
(11, ) - Hauling material for rut filling
(12, ) - Shoulder maintenance
The second subscript indicates the type of equipment most closely associated with the operation:

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</table>

Miscellaneous Other Variables

**BLDDR-** Number of Equivalent 1600 kg. vehicles per blading during dry season.

**BLDWT-** Number of equivalent 1600 kg. vehicles per blading rest of year.

**FREQD-** Frequency of blading earth or gravel surface during dry season (bladings per year).

**FREQS-** Number of vehicles per shoulder blading.

**FREQW-** Frequency of blading earth or gravel surface during rest of year (bladings per year).

**KEQ-** Total cost of maintenance equipment per section per year.

**KLABR-** Total cost of maintenance labor per section per year.

**KLEM-** Total cost of labor, equipment and material per section per year.

**KMAT-** Total cost of maintenance material per section per year.

**KXYZ-** Cost for labor, equipment and material per year for the section being analyzed.

**RCOND-** Road surface conditions. Reference description of subprogram INITL.
SED- Cubic meters of sediment deposited in ditches and culverts of one kilometer of road.

SXYZ- Quantities of labor, equipment and material (XYZ) per kilometer per year.

SXYZE- Quantities of labor equipment and material per year for the section being analyzed.

UXYZ- Unit prices for labor, equipment and materials.
APPENDIX E

LISTING OF FORTRAN STATEMENTS THAT MAKE UP MAINTENANCE MODEL
SUBROUTINE MAINT (YR,RECON)

ROADWAY MAINTENANCE REQUIREMENTS AND COSTS

INTEGER YR
INTEGER RDTYP, SHTYP
INTEGER RBLD(11), RECON(25), OSWTH(3)
REAL MAPOL(20), HDIST(10), MARK(32)
REAL IMPS, IRFCW, NB
REAL KMCA, KMAT, KLBR, KEQ, KLEM
REAL KEMG, KEWT, KERL, KEDT, KELD, KETR, KEDS, KLC, KLTD, KLED, KLF, KMG,
1 KPW, KMP, KMD, KMB
REAL MRCX, MRD, MRDK
REAL KK
REAL MTLST
REAL EH(12,7), LC(12,7), LEO(12,7), LF(12,7), LTD(12,7),
1 MP(12,7), MHA(12,7), MCA(12,7), MD(12,7), MG(12,7), MP(12,7),
2 MW(12,7), LG(12,7)
REAL LOS, MOS
REAL MTCT(25), MUC(25)
DIMENSION DRAIN(7)
DIMENSION ALIGN(3), PROF(54), TEMPL(15), PAVE(12), RCOND(13),
1 DEMAN(7,3), TRAF(7), ECON(4), TOPOG(205), GOLGY(3), GRDCV(4),
2 DRN(8), PROD(54), ECONO(32), VEH(7,12), OUTPT(150), WORK(40)
DIMENSION EFFHK(6)
DIMENSION EQUIV(7)
COMMON ALIGN, PROF, TEMPL, PAVE, RCOND, DEMAN, TRAF, NPER, ECON, MAPOL,
1 RBLD, TOPOG, GOLGY, CBM, GRDCV, ORN, HDIST, PROD, MUC, ECONO, MARK, NUVEH,
2 VEH, OUTPT, WORK, OSWTH
EQUIVALENCE (DRAIN(1), DRN(2))
EQUIVALENCE (WORK(40), YINOX)
EQUIVALENCE (WORK(25), PSI), (WORK(26), THICK)
EQUIVALENCE (MTCT(1), OUTPT(76))

DATA AE/5,
C DEPTH OF GRAVEL WATERED DATA AG1,AG2/5,5/
C DEPTH OF BLADING DATA BD/3/
C PATCHING OPERATION CONSUMPTION DATA CCM1,CCM2/7,3/
C DISTRIBUTOR CONSUMPTION DATA CD1,CD2/7,1/
C COEFFICIENT OF TRACTION OF DRY ROAD DATA CFDR/6/
C MOTOR GRADER CONSUMPTION DATA CMG1,CMG2/15,1/
C LOADER CONSUMPTION DATA CL1,CL2/12,1/
C RATIO OF FOREMAN TIME TO GREASER TIME DATA CLF/2/
C RATIO OF GREASER TIME TO TRUCKDRIVER AND OPERATOR TIME DATA CLG/2/
C ROLLER CONSUMPTION DATA CLR1,CLR2/5,1/
C RUT PATCHING CONSUMPTION DATA CRF1,CRF2,CRF3,CRF4,CRF5/1,.7,.25,.2/.2/
C SEALING OPERATION CONSUMPTION DATA C51,C52,C53,C54/1,4,1,4,4,3/
C DUMP TRUCK CONSUMPTION DATA CT1,CT2/7,1/
C WATER TRUCK CONSUMPTION DATA CWT1,CWT2/9,1/
C MOWER CONSUMPTION DATA CV1,CV2/4,1/
C DENSITY OF COMPACTED GRAVEL DATA DCG/2.24/
C ANNUAL DECREASE OF COEFFICIENT OF TRACTION OF WET PAVEMENT DATA DFRC/0.03/
C DENSITY OF LOOSE GRAVEL DATA DLG/1.8/
C AVERAGE DEPTH OF PATCHES (CM.)
DATA DOP/5./ 00017790
C FINAL COEFFICIENT OF TRACTION OF WET PAVEMENT
DATA FFCW/.3/ 00017810
C NUMBER OF VEHICLES PER SHLD. BLADING
DATA FREQs/500./ 00017820
C GRAVEL LOST PER ADT (TONS/KILOMETER-YEAR)
DATA GL/ .896/ 00017830
C INITIAL COEFFICIENT OF TRACTION OF WET PAVEMENT
DATA IFRCW/.6/ 00017840
C PERCENT OF PATCHING AND RUT REPAIR REQD. FOR SHOULDER
DATA MOS/ .1/ 00017850
C NUMBER OF PASSES NEEDED TO BLADE
DATA PASS1, PASS2/ 2., 4./ 00017860
C LABOR EFFICIENCY
DATA PCL/ , .75/ 00017870
C DISTRIBUTOR PRODUCTION
DATA PD2/ .75/ 00017880
C MOTOR GRADER PRODUCTION
DATA PMG1, PMG2, PMG3/ 2., 4., 75, 6., 0./ 00017890
C LOADER PRODUCTION
DATA PL1, PL2/ 30., 75/ 00017900
C ROLLER PRODUCTION
DATA PR1, PR2, PR3, PR4, PR5/ 2., 75, 6., 3., 5./ 00017910
C DUMP TRUCK PRODUCTION
DATA PT1, PT2, PT3, PT4, PT5, PT6/ 3., 75, 40., 5., 2., 5./ 00017920
C MOWER PRODUCTIVITIES
DATA PV1, PV2, PV3/ 1., 8., 75, 5./ 00017930
C WATER TRUCK PRODUCTION
DATA PWT1, PWT2, PWT3, PWT4, PWT5, PWT6, PWT7/ 6., 75, 40., 10., 20., 4., 2./ 00017940
C ROLLING RESISTANCE OF BITUMINOUS ROADS
DATA ROLL/ .01 / 00017950
C AGGREGATE RATE FOR SEAL (K. / SQ. METERS)
DATA SA/ 14./ 00017960
C ASPHALT RATE FOR SEAL (LITERS/ SQ. METER)
DATA SB/ 1., 2/ 00017970
C PERCENT INCREASE IN BIT. SHLD. MAINT. REQD. BY 1 M, LESS ROADWAY 00018150
C DATA SBI/,.5/ 00018160
C PERCENT INCREASE IN GRAVEL SHLD. MAINT. REQD. BY 1 M, LESS ROAD 00018170
C DATA SGI/,.5/ 00018180
C DEPTH TO REGRAVEL 00018190
C DATA TCR/10. / 00018200
C DEPTH WHEN GRAVEL ROAD BREAKS UP 00018210
C DATA TSC/7. / 00018220
C WATER NEEDED FOR BLADING 00018230
C DATA WA1,WA2,WA3/,.04,.04,.02/ 00018240
C IPRNT=6 00018250
C RDTYP = PAVE(1) + .01 00018260
C
C C INITIALIZE COST MATRICES
DO 290 I = 1,12 00018290
DO 291 J = 1,7 00018300
       EHN(I,J) = 0. 00018310
       LC(I,J) = 0. 00018320
       LEO(I,J) = 0. 00018330
       LF (I,J) = 0. 00018340
       LG(I,J) = 0. 00018350
       LTD(I,J) = 0. 00018360
       MB(I,J) = 0. 00018370
       MBA(I,J) = 0. 00018380
       MCA(I,J)=0 00018390
       MD(I,J) = 0. 00018400
       MG(I,J) = 0. 00018410
       MP(I,J) = 0. 00018420
       MW(I,J) = 0. 00018430
       MTCT(I) = 0. 00018440
291 CONTINUE 00018450
290 CONTINUE 00018460
DO 2931 I = 1,25 00018470
       MTCT(I) = 0. 00018480
C UNIT PRICES 00018490
C UEDS=MUC(1) 00018500
MAINTENANCE POLICY

UDEY = MUC(2)
UED = MUC(3)
UEMG = MUC(4)
UEPL = MUC(5)
UERT = MUC(6)
UEWT = MUC(7)
ULC = MUC(8)
ULF = MUC(9)
ULM = MUC(10)
ULTD = MUC(11)
UMB = MUC(12)
UMBA = MUC(13)
UMCA = MUC(14)
UMD = MUC(15)
UMC = MUC(16)
UMP = MUC(17)
UMW = MUC(18)
CONTINUE

MAINTENANCE POLICY

DSWTH = MAPOL(1)
REGRL = MAPOL(2)
SWTCH = MAPOL(3)
VSWTH = MAPOL(4)
BLADE = MAPOL(5)
FBLOR = MAPOL(6)
FRLWT = MAPOL(7)
FREQM = MAPOL(8)
FRF = MAPOL(9)
FTP = MAPOL(10)
FTS = MAPOL(11)
MRD = MAPOL(12)
DISCM = HDIST(9)
DISG = HDIST(8)
DI SW = HDIST(7)
DRY=DRAIN(1)  
IMPS=DRAIN(2)  
LOS=ALIGN(1)  
SHTYP=PAVE(9)+.01  
THICK=PAVE(4)*100.  
WOD=TEMPL(5)+TEMPL(7)  
WOS=TEMPL(1)*2.  
WOSH=TEMPL(3)  

C  
EFTHK(1)=.44  
EFTHK(2)=.20  
EFTHK(3)=.20  
EFTHK(4)=.14  
EFTHK(5)=.11  
EFTHK(6)=.07  

WHAT IS ROAD TYPE  
EARTH = 1, GRAVEL = 2, PAVED = 3  

IF (RDTPY=2) 1001,1002,1003  

CONTINUE  

CALCULATE BLADINGS IN WET + DRY SEASONS  
BLADINGS SPECIFIED BY N/YEAR SAY BLADE = 1  
BLADINGS SPECIFIED BY EQVEH/BLADE SAY BLADE = -1  
LENGTH OF DRY SEASON = DRY  
# BLADINGS AS SPECIFIED ABOVE = FBLDR IF DRY  
# BLADINGS AS SPECIFIED ABOVE = FBLWT IF WET  

EQVEH = 0.  
DO 361 I=1,NUVEH  
361  
EQVEH=VFH(I,2)*TRA F(I)/1600. + EQVEH  
IF (BLADE)=21,21,20  
EQUIV VEH, PER BLADING DURING WET SEASON  
RBLWT=(12-DRY-IMPS)/12.*(EQVEH*365.)/FBLWT  
EQUIV VEH, PER BLADING DURING DRY SEASON  
RBLDR=DRY/12.*(EQVEH*365.)/FBLDR
FREQW = FBLWT
FREQD = FBLDR
GO TO 22
C
NUMBER OF BLADING PER WET SEASON
BLDWT = FBLWT
C
NUMBER OF BLADING PER DRY SEASON
BLDDR = FBLDR
FREQD = (1.0/FBLDR) * EQVEH * DRY/12. * 365.
GO TO 22
C
CALCULATE ROAD CONDITIONS
RCIND(7) = DRY/12,
RCOND(8) = (12.0 - DRY - IMP)/12.
RCOND(9) = IMP/12.
C
DRY EARTH ROAD CONDITIONS
IF(BLDDR - 2000.) 24, 24, 23
IF(BLDDR - 8000) 25, 25, 26
IF(BLDDR - 20000.26, 26, 726
24 CONTINUE
RCOND(1) = 0.015
RCOND(4) = 0.5
RCOND(10) = 300.
GO TO 23
25 CONTINUE
RCOND(1) = 0.000017 * BLDDR + 0.012
RCOND(4) = 0.57 - (0.00033 * BLDDR)
RCOND(10) = 0.04 * BLDDR + 200.
GO TO 23
26 CONTINUE
RCOND(1) = 0.025
RCOND(4) = 0.3
RCOND(10) = 0.04 * BLDDR + 200.
GO TO 23
726 RCOND(1) = 0.025
RCOND(4) = 0.3
RCOND(10) = 1000.
2331 CONTINUE
C EARTH ROAD CONDITIONS BETWEEN DRY AND RAINY SEASON (12-DRY-IMPS)
IF (BLDWT - 20000.) 28, 28, 27
IF (BLDWT - 20000.) 29, 29, 729
729 IF (BLDWT - 20000.) 30, 30, 730
28 CONTINUE
RCOND(2) = .02
RCOND(5) = .3
RCOND(11) = 300.
GO TO 2881
29 CONTINUE
RCOND(2) = .000017*BLDWT + .017
RCOND(5) = .37*.000033*BLDWT
RCOND(11) = .04*BLDWT + 200.
GO TO 2881
30 CONTINUE
RCOND(2) = .03
RCOND(5) = .1
RCOND(11) = .04*BLDWT + 200.
GO TO 2881
730 RCOND(2) = .03
RCOND(5) = .1
RCOND(11) = 1000.
GO TO 2881
2881 CONTINUE.
C EARTH ROAD CONDITIONS DURING RAINY SEASON (IMPS)
RCOND(3) = .2
RCOND(6) = .1
RCOND(12) = 700.
C
C BLADING REQUIREMENTS
C DRY SEASON
C OPERATIONS ARE = BLADING WITH MOTOR GRADER
C AFTER PASSAGE OF A WATER TRUCK, WITH ROLLING TO BE DONE
C AFTER GRADING
C COSTS OF 1 WATERING , BLADING, ROLLING
C NO OF MOTOR GRADER PASSES TO BLADE ROAD
\[
\begin{align*}
\text{INTGR} &= \text{WOS}/\text{PMG}1 \\
\text{GP} &= \text{PASS}1\cdot(\text{INTGR}+1) \\
\text{C TIME NEEDED TO BLADE} &= \text{EHN}(1,1) = \text{GP}/(\text{PMG}2 \cdot \text{PMG}3) \\
\text{C OPERATOR TIME} &= \text{LEO}(1,1) = \text{EHN}(1,1) \cdot \text{CMG}2 \\
\text{C LITERS OF FUEL REQD} &= \text{MD}(1,1) = \text{EHN}(1,1) \cdot \text{CMG}1 \\
\text{C WATER TRUCK} &= \text{C TIME TO UNLOAD} \\
\text{TU} &= (\text{PWT}1 \cdot 100 \cdot 60 \cdot \text{PWT}7)/(\text{PWT}4 \cdot \text{DCG} \cdot 1000 \cdot \text{PWT}6 \cdot \text{WA}1 \cdot \text{AE}) \\
\text{C CUBIC METRES OF WATER PER KILOMETER} &= \text{MW}(1,2) = \text{WDS} \cdot \text{DCG} \cdot \text{WA}3 \cdot \text{AE} \cdot 100 \\
\text{C TRIP TIME} &= \text{TC} = \text{TU} + \text{PWT}5 + (\text{DISW} \cdot 60 \cdot \text{PWT}2)/\text{PWT}3 \\
\text{C PRODUCTIVITY OF WATER TRUCK} &= \text{PWT} = 60 \cdot \text{PWT}1 \cdot \text{PWT}2/\text{TC} \\
\text{C HOURS OF WATER TRUCK TIME} &= \text{EHN}(1,2) = \text{MW}(1,2)/\text{PWT} \\
\text{C HOURS OF OPERATOR TIME} &= \text{LTD}(1,2) = \text{EHN}(1,2) \cdot \text{CWT}2 \\
\text{C LITERS OF GASOLINE REQD} &= \text{MP}(1,2) = \text{EHN}(1,1) \cdot \text{CWT}1 \\
\text{C ROLLER REQUIREMENTS} &= \text{INTGR}= \text{WOS} \cdot \text{PR}4 / \text{PR}1 \\
\text{RPX} &= \text{INTGR} + 1 \\
\text{CONTINUE} &= 00019850 \\
\text{C HOURS OF ROLLER TIME} &= \text{EHN}(1,3) = \text{RPX} / (\text{PR}2 \cdot \text{PR}3) \\
\text{C OPERATOR TIME} &= \text{LEO}(1,3) = \text{EHN}(1,3) \cdot \text{CR}2 \\
\text{C FUEL USED} &= \text{MP}(1,3) = \text{EHN}(1,3) \cdot \text{CR}1 \\
\text{C END OF DRY ROAD SECTION} &= 00020190 \\
\end{align*}
\]
WET ROAD REQUIREMENTS

OPERATIONS BLADE ROAD WITH MOTORGRADER, COSTS SAME AS BLADING DRY

IT IS NOT NECESSARY TO ROLL OR ADD WATER

MOTORGRADER

TIME NEEDED TO BLADE

EHN(5,1) = EHN(1,1)

OPERATOR TIME

LEO(5,1) = LEO(1,1)

FUEL

MD(5,1) = MD(1,1)

END OF WET EARTH ROAD REQUIREMENTS

THE COSTS FOR WET AND DRY EARTH ROADS ARE FOR ONE BLADING CYCLE ONLY, COSTS FOR THE ENTIRE YEAR WILL NOW BE FOUND

DRY ROAD COSTS = COST OF 1 CYCLE \* FREQD

MOTORGRADER

EHN(1,1) = EHN(1,1) \* FREQD

LEO(1,1) = LEO(1,1) \* FREQD

MD(1,1) = MD(1,1) \* FREQD

WATER TRUCK

MW(1,2) = MW(1,2) \* FREQD

EHN(1,2) = EHN(1,2) \* FREQD

LTD(1,2) = LTD(1,2) \* FREQD

MP(1,2) = MP(1,2) \* FREQD

ROLLER

EHN(1,3) = EHN(1,3) \* FREQD

LEO(1,3) = LEO(1,3) \* FREQD

MP(1,3) = MP(1,3) \* FREQD

WET ROAD

MOTORGRADER

EHN(5,1) = EHN(5,1) \* FREQW

LEO(5,1) = LEO(5,1) \* FREQW

MD(5,1) = MD(5,1) \* FREQW

END OF EARTH ROAD MAINTENANCE SECTION

GO TO DRAINAGE SECTION

GO TO 458
CONTINUE
GRAVEL MODEL
CALCULATE BLADINGS IN WET + DRY SEASONS
BLADINGS SPECIFIED BY N/YEAR SAY BLADE = 1
BLADINGS SPECIFIED BY EQVEH/BLADE SAY BLADE = -1
LENGTH OF DRY SEASON = DRY
# BLADINGS AS SPECIFIED ABOVE = FBLDR IF DRY
# BLADINGS AS SPECIFIED ABOVE = FBLWT IF WET
EQVEH = 0.
DO 3601 I = 1,NUVEH
3601 EQVEH = VEH(I,2) * TRAF(I)/1600. + EQVEH
IF(BLADE) 221, 221, 220
220 BLDWT = (12-DRY) / 12. * (EQVEH*365.) / FBLWT
BLDDR = DRY/12. * (EQVEH*365.) / FBLDR
FREQW = FBLWT
FREQD = FBLDR
GO TO 222
221 FREQD = (1./FBLDR)*EQVEH*DRY/12.*365.
FREQW = (1./FBLWT)*EQVEH*(12.-DRY)/12.*365.
BLDWT = FBLWT
BLDDR = FBLDR
GO TO 222
CALCULATE ROAD CONDITIONS
RCOND(7) = DRY/12.
RCOND(8) = (12.-DRY-IMPS)/12.
RCOND(9) = IMPS/12.
DRY GRAVEL ROADS CONDITIONS
IF(BLDDR< 3000.) 228, 228, 227
227 IF(BLDDR<12000.) 229, 229, 7229
7229 IF(BLDDR<22000.) 230, 230, 7230
228 CONTINUE
RCOND(1) = .015
RCOND(4) = .6
RCOND(10) = 300.
GO TO 228
CONTINUE
RCOND(1) = .0000011*BLDDR + .012
RCOND(4) = .7 - (.000033*BLDDR)
RCOND(10) = 240 + .03*BLDDR
GO TO 2288
CONTINUE
RCOND(1) = .025
RCOND(4) = .3
RCOND(10) = 240 + .03*BLDDR
GO TO 2288
CONTINUE
RCOND(1) = .025
RCOND(4) = .3
RCOND(10) = 900.
GO TO 2251
CONTINUE
RCOND(3) = .02
RCOND(6) = .5
RCOND(12) = 300.
GO TO 2251
CONTINUE
RCOND(3) = .0000011*BLDWT + .017
RCOND(6) = .6 - .000033*BLDWT
RCOND(12) = 240 + .03*BLDWT
GO TO 2251
CONTINUE
RCOND(3) = .03
RCOND(6) = .2
RCOND(12) = 240 + .03*BLDWT
GO TO 2251
CONTINUE
RCOND(3) = .03
RCOND(6) = 2
RCOND(12) = 900.

CONTINUE

SURFACE CONDITION BETWEEN DRY AND IMPS

RCOND(2) = (RCOND(1) + RCOND(3)) / 2.
RCOND(5) = (RCOND(4) + RCOND(6)) / 2.
RCOND(11) = RCOND(12)

BLADING REQUIREMENTS

OPERATIONS ARE = BLADING WITH MOTOR GRADER

AFTER PASSAGE OF A WATER TRUCK, WITH ROLLING TO BE DONE

AFTER GRADING

COSTS OF 1 WATERING, BLADING, ROLLING

NO OF MOTORGRADER PASSES TO BLADE ROAD

INTGR = WOS / PMG1

GP = PASS1 *(INTGR + 1)

TIME NEEDED TO BLADE

EHN(1,1) = GP / (PMG2 * PMG3)

OPERATOR TIME

LDG(1,1) = EHN(1,1) * CMG2

LITERS OF FUEL REQD

MD(1,1) = EHN(1,1) * CMG1

WATER TRUCK

TIME TO UNLOAD

TU = (PWT1 * 100.0 * 60.0 * PWT7) / (PWT4 * DCG * 1000.0 * PWT6 * WA1 * AG1)

CUBIC METRES OF WATER PER KILOMETER

MW(1,2) = WOS * DCG * WA1 * AG1 * 10.

TRIP TIME

TC = TU + PWT5 + (OISH * 60.0 * 2.0 / PWT3)

PRODUCTIVITY OF WATER TRUCK

PWT = 60.0 * PWT1 / PWT2 / TC

HOURS OF WATER TRUCK TIME

EHN(1,2) = MW(1,2) / PWT

HOURS OF OPERATOR TIME

LTD(1,2) = EHN(1,2) * CWT2

LITERS OF GASOLINE REQD.
MP(1,2) = EHN(1,2)*CWT1
C ROLLER REQUIREMENTS
INTGR = WDS*PR4/PR1
RPX = INTGR +1,
C HOURS OF ROLLER TIME
EHN(1,3) = RPX /(PR2*PR3)
C OPERATOR TIME
LEO(1,3) = EHN(1,3) * CR2
C MATERIAL USED
MP(1,3) = EHN(1,3)*CR1
C END OF DRY ROAD SECTION
CONTINUE
C C WET ROAD REQUIREMENTS
C OPERATIONS BLADE ROAD WITH MOTORGRADER, COSTS SAME AS BLADING DRY
C IT IS NOT NECESSARY TO ROLL OR ADD WATER
C MOTORGRADER
C TIME NEEDED TO BLADE
EHN(5,1) = EHN(1,1)
C OPERATOR TIME
LEO(5,1) = LEO(1,1)
C FUEL
MD(5,1) = MD(1,1)
C END OF WET GRAVEL ROAD REQUIREMENTS
C THE COSTS FOR WET AND DRY GRAVEL ROADS ARE FOR 1
C BLADING CYCLE ONLY, COSTS FOR THE ENTIRE YEAR WILL NOW BE FOUND
C DRY ROAD COSTS = COST OF 1 CYCLE * FREQD
C MOTORGRADER
EHN(1,1) = EHN(1,1)* FREQD
LEO(1,1) =LEO(1,1)*FREQD
MD(1,1)=MD(1,1)*FREQD
C WATER TRUCK
MW(1,2)=MW(1,2)*FREQD
EHN(1,2)=EHN(1,2)*FREQD
LTD(1,2)=LTD(1,2)*FREQD
MP(1,2)=MP(1,2)*FREQD
C ROLLER
EHN(1,3) = EHN(1,3) * FREOQ
LFO(1,3) = LFO(1,3) * FREOQ
MP(1,3) = MP(1,3) * FREOQ

C WET ROAD
C MOTORGRADER
EHN(5,1) = EHN(5,1) * FREQW
LFO(5,1) = LFO(5,1) * FREQW
MD(5,1) = MD(5,1) * FREW

1281 CONTINUE
C END OF TOTAL COSTS FOR YEAR SECTION

C REGRAVELLING
C THIS SECTION DETERMINES IF REGRAVELLING IS REQUIRED
C GRAVEL LOST PER YEAR PER EQUIVALENT VEHICLE PER DAY
C IS EQUAL TO GL * ADT METRIC TONS /KM.
C CALCULATIONS OF EQUIV NO OF VEHICLES
C NVEH IS NO. OF TYPE I VEHICLES PER DAY
C WVEHI IS WEIGHT OF TYPE I VEHICLES
C METRIC TONS LOST PER YEAR PER KM
MTLST = GL * EQVEH

DO 3611 I = 1, NUVEH

3611 EQVEH = VEH(I,2) * TRAF(I) / 1600 * EQVEH
C CENTIMETERS LOST
CENT = 100 * (MTLST / (2.24 * WDS * 1000))
C NEW THICKNESS OF ROAD
THICK = THICK - CENT
C IS REGRAVELLING NECESSARY
IF (THICK - TCR) 459, 459, 458
C DOES USER WISH TO REGRAVEL ROAD YES REGRL = 1, NO REGRL = -1
C REGRAVELLING IS DESIRABLE
459 CONTINUE
IF (OSWTH(2) - 1) 501, 501, 500
500 WRITE(IPRNT, 5001)
FORMAT(1HO,' REGRAVELLING REQUIRED')
CONTINUE
C HAS ROAD BROKEN UP
IF (THICK-TSC) 401,401,402
CONTINUE
C ROAD HAS BROKEN UP
IF(REGRL) 403,403,404
RDTYP = 1
PAVE(1) = 1,
C REGRAVELLING NOT DESIRED, ROAD WILL BE TREATED AS AN EARTH ROAD
GO TO DRAINAGE SECTION
GO TO 458
CONTINUE
C ROAD HAS NOT BROKEN UP
IF (REGPL) 405,405,404
RDTYP = 2
C REGRAVELLING NOT DESIRED, ROAD WILL CONTINUE TO BE TREATED
GO TO DRAINAGE SECTION
GO TO 458
CONTINUE
C REGRAVELLING IS TO BE PERFORMED
NO. OF PASSES REQUIRED TO BLADE
INTGR = WOS/PMG1
SP = PASS2*(INTGR+1)
CONTINUE
C MOTOR GRADER REQUIREMENTS
EHN (2,1) = SP/(PMG2*PMG3)
C OPERATOR
LEO(2,1) = EHN(2,1)*CMG2
C FUEL REQUIRED
MD(2,1) = EHN(2,1)*CMG1
C WATER TRUCK REQUIREMENTS
C CUBRIC METERS WATER
1 MW(2,2)=WOS*1000.*DCG*WA2*(AG2+BD)/100.
C TIME TO UNLOAD
TU = PWT1 * 1000.0 * 60.0 * PWT7 / (PWT4 * DCG * 100.0 * PWT6 * WAI * AG2)

C
TRIP TIME
TC = TU + PWT5 + (DISW * 60.0 * 2.0 / PWT3)
C
PRODUCTIVITY
PWT = 60.0 * PWT1 * PWT2 / TC
C
HOURS OF WATER TRUCK TIME
EHN(2, 2) = MW(2, 2) / PWT
C
HOURS OF OPERATOR TIME
LTD(2, 2) = EHN(2, 2) * CWT2
C
FUEL
MP(2, 2) = EHN(2, 2) * CWT1
C
ROLLER REQUIREMENTS FOR REGRAVELLING
PASSES REQD
INTGR = WOS * PR5 / PR1
RP = INTGR + 1.0
C
HOURS NEEDED TO ROLL
EHN(2, 3) = RP / (PR2 * PR3)
C
HOURS OF OPERATOR TIME
LEC(2, 3) = EHN(2, 3) * CR2
C
CONTINUE
FUEL
MP(2, 3) = EHN(2, 3) * CR1
C
DUMP TRUCK TIME
C
GRAVEL NEEDED PER KILOMETRE
MG(2, 4) = WOS * AG2 * DCG * 10.0
C
TIME FOR 1 ROUND TRIP
RT = (PT4 + PT5 + PT6 + (DISG * 2.0 * 60.0 / PT3)) / 60.0
C
PRODUCTIVITY PER TRUCK
PDT = PT2 * PT1 / RT
C
TRUCK TIME
EHN(2, 4) = MG(2, 4) * 1.0 / PDT
C
DRIVER TIME
LTD(2, 4) = EHN(2, 4) * CT2
C
FUEL
MP(2, 4) = EHN(2, 4) * CT1
C
LOADER REQUIREMENTS FOR REGRAVELLING
C LOADER TIME
EHN(2,5) = MG(2,4) * (PL1 * PL2 * DLG)
C OPERATOR TIME
LEC(2,5) = EHN(2,5) * CL2
C DIESEL FUEL
MD(2,5) = EHN(2,5) * CL1
C CALCULATE NEW GRAVEL THICKNESS
THICK = THICK + AG
GO TO 459
C END OF REGRAVELLING SECTION

1003 CONTINUE
C BITUMINOUS PAVEMENT MAINTENANCE
C PREDICTION OF DETERIORATION, MAINTENANCE DEMAND, AND IMPROVEMENT
C OBTAINED BY MAINTENANCE
C INITIALIZATION OF PAVEMENT CONDITIONS
IF (YR-1.01) 91, 91, 92
CONTINUE
PSI = 4.2
YINDX = 0
92 IF (RECON(YR-1)) 93, 93, 94
CONTINUE
PSI = 4.2
YINDX = 0
94 CONTINUE
C SUBROUTINE DETER CALCULATES THE ANNUAL DROP IN PSI DUE TO
C TRAFFIC, ENVIRONMENTAL FACTORS AND AGE
CALL DETER (DEL, VEH, PAVE, CBR, PSI, OSWTH, YINDEX, TRAF, EFTHK, 1
NUVEH )
C PSI AT START OF YEAR
PSIK = PSI
C VALUE OF SURFACE PARAMETERS AT START OF YEAR 00023630
C SQUARE ROOT OF C+P PER 1000 SQ. METERS 00023640
IF(PSIK-3.6)376,376,375 00023650
375 CPRTK=0. 00023660
GO TO 374 00023670
376 CPRTK=(PSIK-3.6)/(-.069) 00023680
374 CONTINUE 00023690
C MEAN SLOPE VARIANCE 00023700
SVK = 10.*((PSIK-5.5)/(-2.9)) -1. 00023710
C MEAN RUT DEPTH (INCHES) 00023720
MRDK=1.-18*PSIK 00023730
C SERVICEABILITY AFTER DETERIORATION AND BEFORE MAINTENANCE 00023740
PSI=PSI-DEL 00023750
PSII=PSI 00023760
C VALUES OF SURFACE PARAMETERS AFTER TRAFFIC AND BEFORE MAINTENANCE 00023780
IF(PSI-3.6)378,378,377 00023790
377 CPRT=0. 00023800
GO TO 379 00023810
C SQUARE ROOT OF C+P PER 1000 SQ METERS 00023820
378 CPRT=(PSI-3.6)/(-.069) 00023830
379 CONTINUE 00023840
C SLOPE VARIANCE BEFORE MAINTENANCE 00023850
SV=10**((PSIK-5.5)/(-2.9))-1 00023860
C RUT DEPTH BEFORE MAINTENANCE 00023870
RD=1.-18*PSI 00023880
C CHANGE IN SURFACE PARAMETERS DUE TO TRAFFIC 00023890
C SQUARE METERS OF NEW CRACKING PER KILOMETER OF ROAD 00023900
DELCP=((CPRTK-CPRK)-CPRT-CPRK)*WGS 00023910
C INCREASE IN SLOPE VARIANCE 00023920
DELSV=SVK-SV 00023930
C INCREASE IN MEAN RUT DEPTH (INCHES) 00023940
DELRD=MRDK-RD 00023950
C MAINTENANCE WORK DONE THIS YEAR 00023960
C AREA PATCHED PER KILOMETER OF ROAD (IN SQ. METERS) 00023970
SMP=FTP*(-DELCP) 00023980
C AREA SEALED PER KILOMETER OF ROAD (IN SQ. METERS) 00023990
00024000
00024010
00024020
00024030
00024040
00024050
00024060
00024070
SMS=FTS*(-DELCP)

C CUBIC METERS OF PUT FILLING PER KILOMETER

IF(RD-(MRD/2.54))3001,3001,3000

3800 CMPR=50.0*FRF*RD=2.54

GO TO 391

C

3801 CMPR=0

C IMPROVEMENT IN SURFACE PARAMETERS AS A RESULT OF MAINTENANCE WORK

390 FIXRD=0.

GO TO 392

391 FIXRD=0.5*FRF*RD

C

392 FIXCP=.5*SMS/WOS

C CHECK ON AMOUNT OF CRACKING AND PATCHING

IF( CPRT-5.) 393,393,394

393 KK = 0

GO TO 397

394 IF ( CPRT-10.) 395,395,396

395 KK = .5

GO TO 397

396 KK = 1

397 CONTINUE

FIXSV = .3*FTP*SV*KK

C NEW VALUES OF SURFACE PARAMETERS AFTER MAINTENANCE

CPRTX= ( CPRT*CPRT-FIXCP) **.5

C

SVX=SV-FIXSV

MRDX=RD-FIXRD

C VALUE OF SERVICEABILITY AFTER MAINTENANCE

PSI=5.03-1.91*43*ALOG(1.0+SVX)-.001*CPRTX-1.38*(MRDX**2).

C

IF(OSWTH(2)-1)505,505,504

504 CONTINUE
WRITE (IPRNT, 7116) PSI, PSI, SV, SVX, RD, MRDX, CPRT, CPRTX 24422
7116 FORMAT (HO, TI0, ' BEFORE MAINTENANCE', TI45, ' AFTER MAINTENANCE'// 24423
1 ' PSI', F5.2, T45, F5.2: ' SLOPE VARIANCE', E10.2, T45, E10.2: ' RUT DE 24424
2 PTH(CM)', F5.2, T45, F5.2: ' CRACKING AND PATCHING (SQ M PER 1000 SQ 24425
3 METERS) ', T12, F10.2, T45, F10.2 ) 24426
505 CONTINUE 00024450
CC PREPARED SURFACE CONDITIONS FOR YEAR 00024480
C PAVED ROAD CONDITION DURING DRY SEASON (DRY) 00024490
RCOND(1) = ROLL 00024500
RCOND(4) = CFDR 00024510
C ROUGHNESS IN INCHES PER MILE 00024520
RCOND(10) = (5.0 - (PSI + PSI + PSI) / 3.0) / .015 00024530
C PAVED ROAD CONDITIONS BETWEEN DRY AND RAINY SEASON (12 - DRY - IMPS) 00024540
RCOND(2) = ROLL 00024550
RCOND(5) = CFDR 00024560
RCOND(11) = RCOND(10) 00024570
C PAVED ROAD CONDITIONS DURING RAINY SEASON (IMPS) 00024580
RCOND(3) = ROLL 00024590
RCOND(6) = IFRCW - YR * DFRC 00024600
RCOND(12) = RCOND(10) 00024610
IF (FFRCW - RCOND(6)) < 1341, 1341, 1342 00024620
1341 RCOND(6) = FFRCW 00024630
1342 CONTINUE 00024640
RCOND(7) = DRY / 12 00024650
RCOND(8) = (12 - DRY - IMPS) / 12 00024660
RCOND(9) = IMPS / 12 00024670 00024680
C CC COMPUTATION OF LABOR, EQUIPMENT AND MATERIAL REQUIRED FOR 00024690
C PAVEMENT MAINTENANCE 00024700
CC OPERATION PLACE AND COMPACT BITUMINOUS PATCHING 00024710
C OF COLD MIX AS DEEP OR SKIN PATCHES 00024720
EHN(6, 4) = CCM2 * DOP / PT2 * SMP * .01 00024730
C COMMON LABOR NEEDED 00024740
LC(6, 4) = CCM1 * DOP / PCL * SMP * .01 00024750
C TRUCK DRIVER 00024760
LTD(6, 4) = EHN(6, 4) * CT2 00024770
C FUEL REQUIRED
MP(6,4) = EHN(6,4) * CT1

CC OPERATION: HAUL COLD MIX TO ROAD SECTION

C TIME NEEDED FOR 1 ROUND TRIP
RT = PT4 + PT6 + DISCM * 60 * 2 / PT3

C TRUCK HRS. NEEDED TO HAUL PATCHING MIX FOR ONE KILOMETER OF ROAD
EHN(7,4) = DCG * RT * DOP / (DLG * PT1 * 60 * PT2) * SMP * 0.01

C TRUCK DRIVER HOURS
LTD(7,4) = EHN(7,4) * CT1

C FUEL REQUIRED
MP(7,4) = EHN(7,4) * CT1

CC OPERATION: LOAD COLD MIX INTO TRUCKS

C LOADER TIME
EHN(7,5) = DCG * DOP / (PL1 * PL2 * DLG) * SMP * 0.01

C OPERATOR TIME
LEO(7,5) = EHN(7,5) * CL2

C FUEL
MD(7,5) = EHN(7,5) * CL1

C PREMIXED PATCHING MATERIAL USED
MBA(6,4) = DCG * DOP * SMP * 0.01

CC OPERATION: PLACE AND ROLL BIT. SEAL COAT FOR ONE KILOMETER OF ROAD

C COMMON LABOR REQUIRED
LC(8,4) = CS1 / PCL * SMP * 0.01
EHN(8,4) = CS2 / PT2 * SMP * 0.01

C TRUCK DRIVER
LTD(9,4) = EHN(8,4) * CT2

C DISTRIBUTOR REQUIRED
EHN(8,7) = CS3 / PD2 * SMP * 0.01

C DISTRIBUTOR TRUCK DRIVER
LTD(8,7) = EHN(8,7) * CD2

C ROLLER HOURS
EHN(8,3) = CS4 / PR2 * SMP * 0.01

C ROLLER OPERATOR
LEO(8,3) = EHN(8,3) * CR2

C FUEL FOR TRUCKS, DISTRIBUTOR, ROLLER
MP(8,4) = EHN(8,4) * CT1
\[ \text{MP}(8,7) = \text{EHN}(8,7) \times CD1 \]
\[ \text{MP}(8,3) = \text{EHN}(8,3) \times CR1 \]
\[ \text{CC OPERATION TRANSPORT AGGREGATE FROM SOURCE TO ROAD SECTION} \]
\[ \text{DUMP TRUCK TIME TO MAKE CNG ROUND TRIP} \]
\[ \text{RT} = \text{PT4} + \text{PT6} + \text{DISCM} \times 60 \times 2 / \text{PT3} \]
\[ \text{HOURS NEEDED FOR SEALING ON ONE KILOMETER OF ROAD} \]
\[ \text{EHN}(9,4) = \text{SA} \times 100 \times \text{RT} / (\text{DLG} \times \text{PT1} \times 60 \times 1000) \times \text{SMS} \times 0.01 \]
\[ \text{DRIVER TIME} \]
\[ \text{LTD}(9,4) = \text{EHN}(9,4) \times CT2 \]
\[ \text{LOADER TIME} \]
\[ \text{EHN}(9,5) = \text{SA} \times 1 / (\text{DLG} \times \text{PL1}) \times \text{SMS} \times 0.01 \]
\[ \text{LOADER OPERATOR} \]
\[ \text{LEO}(9,5) = \text{EHN}(9,5) \times CL2 \]
\[ \text{MATERIAL} \]
\[ \text{FUEL} \]
\[ \text{MP}(9,4) = \text{EHN}(9,4) \times CT1 \]
\[ \text{MP}(9,5) = \text{EHN}(9,5) \times CL1 \]
\[ \text{AGGREGATE} \]
\[ \text{MCA}(8,4) = 1 \times \text{SA} \times \text{SMS} \times 0.01 \]
\[ \text{LIQUID ASPHALT} \]
\[ \text{MB}(8,4) = \text{SA} \times \text{SMS} \]
\[ \text{CC OPERATION; PLACE AND COMPACT RUT PATCHING MIX PER KILOMETER} \]
\[ \text{COMCEN LABOR} \]
\[ \text{LC}(10,4) = \text{CRF1} / \text{PCL} \times \text{CMPR} \]
\[ \text{DUMP TRUCK} \]
\[ \text{EHN}(10,4) = \text{CRF2} / \text{PT2} \times \text{CMPR} \]
\[ \text{TRUCK DRIVER} \]
\[ \text{LTD}(10,4) = \text{EHN}(10,4) \times CT2 \]
\[ \text{FUEL} \]
\[ \text{MP}(10,4) = \text{EHN}(10,4) \times CT1 \]
\[ \text{MOTOR GRADER} \]
\[ \text{EHN}(10,1) = \text{CRF3} / \text{PMG2} \times \text{CMPR} \]
\[ \text{MOTOR GRADER OPERATOR} \]
\[ \text{LEO}(10,1) = \text{EHN}(10,1) \times \text{CMG2} \]
\[ \text{FUEL} \]
\[ \text{MD}(10,1) = \text{EHN}(10,1) \times \text{CMG1} \]
DISTRIBUTOR
EHN(10,7) = CRF5/PD2 * CMPR

DISTRIBUTOR TRUCK DRIVER LTD(10,7) = EHN(10,7) * CD2

FUEL MP(10,7) = EHN(10,7) * CD1

ROLLER EHN(10,3) = CRF4/PR2 * CMPR

OPERATOR LED(10,3) = EHN(10,3) * CR2

FUEL MP(10,3) = EHN(10,3) * CR1

PATCHING MIXTURE MBA(10,4) = DCG * CMPR

TRANSPORT PATCHING MIXTURE FOR RUTS

TIME FOR ONE ROUND TRIP RT = PT4 + PT6 + DISCM * 60 / 2 / PT3

TRUCK TIME EHN(11,4) = DCG * RT / (DLG * PT1 * PT2 * 60) * CMPR

TRUCK DRIVER LTD(11,4) = EHN(11,4) * CT2

FUEL MP(11,4) = EHN(11,4) * CT1

CONTINUE 138

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE

CONTINUE
C SEDIMENT DEPOSITED
SSF=1.(/TEMPL(9))+1./ (TEMPL(10))+5
TERF=TOPG(4)+TOPG(3)+TOPG(2)*3.
TERF = TERF/100.
SED=6.3+3.3*(15+DRAIN(3))/100.*TERF*SSF
C DUMP TRUCK
EHN(4,4)=SED%24.//(100.*PCL)
C DRIVER
LTD(4,4)=EHN(4,4)*CT2
C FUEL
MP(4,4)=EHN(4,4)*CT1
C MOTORGRADER
EHN(4,1)=SED*6.//(100.*PCL)
C OPERATOR
LEO(4,1)=EHN(4,1)*CMG2
C FUEL
MD(4,1)=EHN(4,1)*CMG1
C COMMON LABOR
LC(4,4)=1.5*SED/PCL
GO TO 457
C
457 CONTINUE
CCC VEGETATION CONTROL
C THIS SECTION COMPUTES THE COST OF MOWING THE NECESSARY SECTIONS
C IS ROADSIDE MAINTENANCE DESIRED
IF (VSWTH) 456,456,4571
4571 CONTINUE
C PASSES NEEDED
IF (PAVE(9)-1.5) 4573,4573,4574
4573 INTGR = (WOD+WOSH)/PV1
GO TO 45751
4574 INTGR= WOD/PV1
45751 CONTINUE
GP = 2 *(INTGR+1)
C MOWER REQUIREMENTS
EHN(3,6)=GP/(PV2*PV3)*FREQM
C OPERATOR TIME
LEO(3,6) = EHN(3,6) * CV2
C FUEL
MP(3,6) = EHN(3,6) * CV1
C END OF VEGETATION CONTROL SECTION
GO TO 456
C
C SHOULDER MAINTENANCE
456 CONTINUE
IF (SWITCH) 455,455,51
51 CONTINUE
C SHOULDER TYPE
IF (2-SHTYP) 70,71,72
70 CONTINUE
C BITUMINOUS SHOULDER MAINTENANCE
IF (WOSH-,1) 455,53,53
53 CONTINUE
C RATIO OF SHOULDER SEALING DEMAND TO ROADWAY SEALING DEMAND
SHA = 2*WOSH/WOS
C FRACTION OF SURFACE PATCHING
FRSH = MOS*(1 + SBI)*(2 - WOS)
C LABOR
LC(12,4) = SHA*LC(8,4) + FRSH*(LC(6,4) + LC(10,4))
C DUMP TRUCK
EHN(12,4) = SHA*(EHN(8,4) + EHN(9,4)) + FRSH*(EHN(6,4) + EHN(7,4) + EHN(10,4) + EHN(11,4))
C TRUCK DRIVER
LTD(12,4) = EHN(12,4) * CT2
C DISTRIBUTOR
EHN(12,7) = SHA*EHN(8,7) + FRSH*EHN(10,7)
C DISTRIBUTOR DRIVER
LTD(12,7) = EHN(12,7) * CD2
C ROLLER
EHN(12,3) = SHA*EHN(8,3) + FRSH*EHN(10,7)
C ROLLER OPERATOR
LEO(12,3) = EHN(12,3) * CR2
C FUEL
MP(12,4) = EHN(12,4) * CT1
MP(12,7) = EHN(12,7) * CD1
MP(12,3) = EHN(12,3) * CR1
C MOTORGRADER
EHN(12,1) = FRSH*EHN(10,1)
EHN(12,7) = EHN(12,7) * CD1
EHN(12,3) = EHN(12,3) * CR1
C MOTORGRADER OPERATOR
LEO(12,1) = EHN(12,1) * CMG2
C LOADER
EHN(12,5) = SHA* EHN(9,5) + FRSH*( EHN(7,5) +EHN(11,5) )
C LOADER OPERATOR
LEO(12,5) = EHN(12,5) * CL2
C FUEL
MD(12,1) = EHN(12,1) * CMG1
MD(12,5) = EHN(12,5) * CL1
C PATCHING MATERIAL
MBA(12,4) = FRSH*( MBA(6,4) + MBA(10,4) )
C AGGREGATE
MCA(12,4) = .1*MCA(8,4)
C LIQUID ASPHALT
MB(12,4) = .1*MBA(8,4)
C CONTINUE
CONT
C GRAVEL SHOULDER MAINTENANCE
C MOTORGRADER TIME TO BLADE SHOULDERS OF 1 KM. OF ROADWAY
EHN(12,1) = 4. /(PMG2*PMG3)
C WIDTH FACTOR
WF = (1. + SGI)**(7. - WOS)
C TRAFFIC FACTOR
SNV = 0.
DO 77 I = 1, NUVEH
SNV = SNV+ TRAF(I)
IF(SNV-FREQS) 771, 771, 772
771 TF= 1.
GO TO 773
772 TF= 1. + (SNV-FREQS)/FREQS
773 CONTINUE
C NO. OF BLADING PER YEAR
NB = TF*WF
C MOTOR GRADER HOURS
EHN(12,1) = EHN(12,1) *NB
C MOTOR GRADER OPERATOR
LEO(12,1) = EHN(12,1) *CMG2
C FUEL
MD(12,1) = EHN(12,1) *CMG1
C ROLLER TIME PER ROLLING
EHN(12,3) = (PR4*2)/(PR2*PR3)
C ROLLER HOURS/ YEAR
EHN(12,3) = EHN(12,3) *NB
C ROLLER OPERATOR
LEO(12,3) = EHN(12,3) *CR2
C FUEL
MP(12,3) = EHN(12,3) *CR1
72 CONTINUE
C EARTH SHOULDER SECTION
455 CONTINUE
DO 919 I = 1,12
DO 920 J = 1,7
LF (I,J) = LC(I,J)*CLF
LG(I,J) = LTD(I,J)*CLG1 + LEO(I,J)*CLG2
920 CONTINUE
919 CONTINUE
C COST SUM SECTION
C ALL MAINTENANCE COSTS HAVE BEEN CALCULATED AT THIS POINT
C THE COSTS WILL NOW BE SUMMED AND THESE SUMS WILL BE
C RETURNED TO THE MAIN PROGRAM
C COST PER KM
C INITIALIZE COST SUM MATRIX
SYZ = QUANTITIES OF XYZ PER KM PER YEAR

MOTORGRADER
SEM G = 0.
CONTINUE
WATER TRUCK
SEWT = 0.
ROLLER
SERL = 0.
DUMP TRUCK
SEDT = 0.
SELD = 0.
TRACTOR AND MOWER HOURS
SETR = 0.
DISTRIBUTOR
SEDS = 0.
SLC = 0.
SLEO = 0.
SLF = 0.
SLG = 0.
SLTD = 0.
SMB = 0.
SMBA = 0.
SMCA = 0.
SMD = 0.
SMG = 0.
SMP = 0.
LOADER
SMW = 0.

DO 301 I = 1,12
DO 300 J = 1,7
SLC = SLC + L C(I,J)
SLEO = SLEO + L EO(I,J)
SLF = SLF + L F(I,J)
SLG = SLG + L G(I,J)
SLTD = SLTD + LTD(I,J)
SMB = SMB + MB(I,J)
SMBA = SMBA + MBA(I,J)
SMCA = SMCA + MCA(I,J)
SMD = SMD + MD(I,J)
SMG = SMG + MG(I,J)
SMP = SMP + MP(I,J)
SMW = SMW + MW(I,J)

300 CONTINUE
301 CONTINUE
C

DO 380 I = 1, 12
   J = 1
   SEMG = SEMG + EHN(I,J)
   J = 2
   SEWT = SEWT + EHN(I,J)
   J = 3
   SERL = SERL + EHN(I,J)
   J = 4
   SEDT = SEDT + EHN(I,J)
   J = 5
   SELD = SELD + EHN(I,J)
   J = 6
   SETR = SETR + EHN(I,J)
   J = 7
   SEDS = SEDS + EHN(I,J)

280 CONTINUE
C
C
C
C
C

SXYZE = QUANTITY OF XYZ USED ON ENTIRE SECTION IN 1 YEAR

C
C
C
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<tr>
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<tr>
<td>SLCE = LOS*SLC</td>
<td></td>
<td>00028010</td>
</tr>
<tr>
<td>SLEOE = LOS*SLEOE</td>
<td></td>
<td>00028020</td>
</tr>
<tr>
<td>SLFE = SLF*LOS</td>
<td></td>
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</tr>
<tr>
<td>SLGE = SLG*LOS</td>
<td></td>
<td>00028040</td>
</tr>
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<td>SLTDE = LOS*SLTDE</td>
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<tr>
<td>SMBE = SMB*LOS</td>
<td></td>
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</tr>
<tr>
<td>SMBAE = SMBA*LOS</td>
<td></td>
<td>00028070</td>
</tr>
<tr>
<td>SMCAE = SMCA*LOS</td>
<td></td>
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<tr>
<td>SMDE = SMD*LOS</td>
<td></td>
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<tr>
<td>SMGE = SMG*LOS</td>
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<tr>
<td>SMWE = S*LOS</td>
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**Capital Costs of Road Maintenance**

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<td>KXYZ</td>
<td>Currency Costs of XYZ for Entire Section</td>
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<tr>
<td>UXYZ</td>
<td>Unit Price of XYZ</td>
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**C CAPITAL C**

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<tr>
<td>KELD</td>
<td>UELD*SELDE</td>
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<td>KEMG</td>
<td>UEMG*SEMGE</td>
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<tr>
<td>KMW</td>
<td>UMW*SMWE</td>
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</table>

**C K**
C  COSTS OF LABOR, EQUIPMENT, AND MATERIALS

KLARD = KLC + KLEO + KLF + KLTD
KEQ = KEDT + KEDS + KELD + KEMG + KER + KEWT
KMAT = KMB + KMA + KMB + KME + KMP + KMW
KLEM = KLABR + KEQ + KMAT

CEND OF COST SUM SECTION

IF (DSWTH(2) - 2) 711, 711, 712

C712 CONTINUE

1011 FORMAT (IHO, 'THE FOLLOWING ARRAYS CONTAIN DETAILED ACCOUNTS OF THE
MAINTENANCE EFFORT';
COLUMNS DEAL WITH EQUIPMENT TYPES, WHILE ROWS REFER TO VARIOUS TASKS;
TASKS ARE ', T100; 'EQUIPMENT TYPES ARE ')

WRITE (IPRNT, 1012)

1012 FORMAT (1X, 'BLADING DURING DRY SEASON', T100, 'MOTOR GRADER';
2 REGRAVELLING', T100, 'WATER TRUCK';
3 VEGETATION CONTROL', T100, 'ROLLER
4 DRAINAGE-CULVERT AND DITCH CLEANING', T100, 'DUMPTUCK';
5 BLADING DURING WET SEASON', T100, 'LOADER';
6 PATCH WITH COLD MIX', T100, 'TRACTOR';
7 HAUL COLD MIX', T100, 'WATER TRUCK';
8 PLACE AND ROLL RETUMINOUS SEALCOAT';
9 HAUL AGGREGATE FOR SEAL COAT';
10 PLACE 2 AND COMPACT PATCHING MIX IN RUTS';
11 HAUL RUT PATCHING MIX';
12 SHOULDER MAINTENANCE ')

WRITE (IPRNT, 1013)

1013 FORMAT (IHO, 'AN ARRAY ELEMENT INDICATES THE PHYSICAL QUANTITY EXPENDED PERFORMING A TASK';
WITH A CERTAIN TYPE OF MACHINERY')

WRITE (IPRNT, 1014)

1014 FORMAT ('EQUIPMENT HOURS BY TASKS')
WRITE (IPRNT, 1015) ((EHN(I, J), J = 1, 7), I = 1, 12)
WRITE (IPRNT, 1016) ((LC(I, J), J = 1, 7), I = 1, 12)
WRITE (IPRNT, 1017) ((LEO(I, J), J = 1, 7), I = 1, 12)
WRITE(IPRNT,1017)
1017 FORMAT('O FOREMAN HOURS')
WRITE(IPRNT,101) (( LF(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1018)
1018 FORMAT('O GREASER HOURS')
WRITE(IPRNT,101) ((LG(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1019)
1019 FORMAT('O TRUCK DRIVER HOURS')
WRITE(IPRNT,101) (( LTD(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1020)
1020 FORMAT('O LITERS OF LIQUID ASPHALT')
WRITE(IPRNT,101) (( LG(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1021)
1021 FORMAT('O COLD MIX (TONS)')
WRITE(IPRNT,101) (( MBA(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1022)
1022 FORMAT('O TONS OF AGGREGATE(PATCHING)')
WRITE(IPRNT,101) (( MCA(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1023)
1023 FORMAT('O LITERS OF DIESEL FUEL')
WRITE(IPRNT,101) (( MD(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1024)
1024 FORMAT('O TONS OF GRAVEL')
WRITE(IPRNT,101) (( MG(I,J), J = 1,7), I = 1,12)
WRITE(IPRNT,1025)
1025 FORMAT('O CUBIC METERS OF WATER')
WRITE(IPRNT,101) (( MW(I,J), J = 1,7), I = 1,12)
101 FORMAT( 'ICH'/(7F10.1 ))
711 CONTINUE
MTCT(1) = KLABR
MTCT(2) = KQO
MTCT(3) = KMAT
MTCT(4) = KLEM
MTCT(5) = SEMG
MTCT(6) = SEWT
MTCT(7) = SERL
MTCT(8) = SEDT
MTCT(9) = SELD
MTCT(10) = SETR
MTCT(11) = SEDS
MTCT(12) = SLC
MTCT(13) = SLEO
MTCT(14) = SLF
MTCT(15) = SLTD
MTCT(16) = SMB
MTCT(17) = SMBA
MTCT(18) = SMCA
MTCT(19) = SMD
MTCT(20) = SMG
MTCT(21) = SMP
MTCT(22) = SMW
MTCT(23) = SLG
RETURN
END
SUBROUTINE DETER (DEL, VEH, PAVE, CBR, PSI, OSWTH, YINDX, TRAF, EFTHK, NUVEH)

THIS ROUTINE CALCULATES THE DROP IN SERVICEABILITY OF A PAVED OR
SURFACE TREATED ROAD

INTEGER NUVEH
INTEGER OUT
INTEGER OSWTH
DIMENSION VEH(7,12), EQUIV(7), PAVE(12), EFTHK(6), TRAF(7), OSWTH(3)

C

AGE ASSOCIATED DETERIORATION RATE
DATA ABOX/, 03/
C
RATE OF DETERIORATION (TRAFFIC INDUCED)
DATA DRATE/1, 1/
C
RATE OF ENVIRONMENT CAUSED DETERIORATION
DATA EROD/0.15/
C
MINIMUM ACCEPTABLE PSI LEVEL
DATA PSLVL/1, 1/
C

OUT = 6
C
CALCULATE AGE OF PAVEMENT
YINDX = YINDX + 1
C
RATE OF DETERIORATION
C
THSE COEFFICIENTS ARE FROM THE AASHO ROAD TEST
EOSWL = 18,
ALPH = .5 x 10 * (.078 * EQSWL - 6)
CONTINUE
BETA = .35 + .005 * EOSWL
C
COMPUTE STRUCTURAL NUMBER OF PAVEMENT
IPAV7 = PAVE(7) + .01
IPAV5 = PAVE(5) + .01
IPAV3 = PAVE(3) + .01
SN = (EFTHK(IPAV7) * PAVE(8) + EFTHK(IPAV5) * PAVE(6) +
1 EFTHK(IPAV3) * PAVE(4)) * 39.4

00023210
00023220
00023230
00023240
00023250
00023260
00023270
00023280
00023290
00023300
00023310
00023320
SN = \text{SN} = \text{SN}^{*}\left(\frac{\text{ALOG(CBR)}}{\text{ALOG(XYZ)}}\right)

S1 = \text{ALPH}^{*}10^{*}*(-\text{BETA}*\text{SN})

C AMOUNT OF DETERIORATION

C THE DETERIORATION DUE TO THE PASSAGE OF A VEH. DEPENDS ON ITS LOAD

C AND NO OF AXLES

C COMPUTE THE NO. OF EQUIVALENT 18 KIP AXLE LOADS IN YEAR I

DO 1446 I = 1, NUVEH

EQUIV(I) = 0.

W2 = VEH(I,3)

W1 = VEH(I,2)* - W2

IF(VEH(I,1) -2.1) 1447, 1447, 1448

1447 CONTINUE

GO TO 1447

1448 IF(VEH(I,1) -3.1) 1449, 1449, 1450

1450 IF(VEH(I,1) -4.1) 1451, 1451, 1452

1449 EQUIV(I) = 10^{*}\left(1.1*W1/454.0-1.8\right) +10^{*}\left(1.1*W2/454.0-1.8\right)

GO TO 1447

1451 EQUIV(I) = 10^{*}\left(1.1*W1/454.0-1.8\right) +10^{*}\left(1.1*W2/454.0-4.5\right)

GO TO 1447

1452 EQUIV(I) = 10^{*}\left(1.1*W1/454.0-4.5\right) +10^{*}\left(1.1*W2/454.0-4.5\right)

1447 CONTINUE

CONTINUE

EOVEH = 0.

DO 1453 I = 1, NUVEH

EOVEH = EQUIV(I)*TRAU(I)*365. + EQVEH

1453 CONTINUE

C THE LOSS OF SERVICEABILITY IS THE PRODUCT OF THE RATE OF

C DETERIORATION AND THE NO OF EQUIVALENT AXLE LOADINGS

DELL = DRATE*S1*EOVEH

C DETERIORATION DUE TO ENVIRONMENTAL EFFECTS

DELL = DELL + EROD

C AGE ACCELERATED DETERIORATION
DEL = DELL*((1+ABDX)**YINDEX)

C PSI AFTER DETERIORATION
PSLE = PSI-DEL

C CHECK ON PSI LEVEL
IF (PSLE-PSLVL) 10,10,20
10 CONTINUE
WRITE(CUT,100) PSLE, YINDEX
100 FORMAT(1H1,'PSI=',F5.2,'ROAD IS ',F5.2,' YEARS OLD'/
1/ ' RECONSTRUCTION SHOULD BE INITIATED' )
20 CONTINUE
IF (OSWTH(2)-1) 331,331,330
330 CONTINUE
WRITE(OUT,1741) EQVEH
1741 FORMAT('O EQUIVALENT 18 KIP AXLE LOADS ', E10.2)
WRITE (OUT,1742) SN123,SN,DEL,DELL,PSLE
1742 FORMAT(1HO,' TRUE STRUCTURAL NO', F10.2/' EFFECTIVE STRUCTURAL NO
1',F10.2/ ' DROP IN PSI',F5.3,' DELL' F5.2//' PSI',F5.2 )
331 CONTINUE
RETURN
END
SUBROUTINE INITL

THIS ROUTINE DETERMINES THE INITIAL ROAD SURFACE CONDITIONS

INTEGER RDTYP
INTEGER RBLD(11), RECCN(25), OSWTH(3)
REAL MAPOL(20), HDIST(10), MARK(32), TEMPS
DIMENSION RCOE(12), RCOG(12), RCOP(12)
DIMENSION DRAIN(7),
DIMENSION ALIGN(3), PROF(54), TEMPL(15), PAVE(12), RCOND(13),
1 DEMAN(7,3), TRAF(7), ECON(4), TOPOG(205), COLGY(3), GRDCV(4),
2 DRN(8), PROD(54), ECONO(32), VEH(7,12), OUTPT(150), WORK(40)

COMMON ALIGN, PROF, TEMPL, PAVE, RCOND, DEMAN, TRAF, NPER, ECON, MAPOL,
1 RBLD, TOPOG, COLGY, CBR, GRDCV, DRN, HDIST, PROD, MUC, ECONO, MARK, NUVEH,
2 VEH, OUTPT, WORK, OSWTH

EQUIVALENCE (DRAIN(1), DRN(2))
DATA RCOE/.02, .4, .2, .4, .2, .1, .1, .1, .25, .25, .700, /
DATA RCOG/.02, .02, .03, .6, .5, .4, .1, .1, .1, .25, .25, .25, /
DATA RCOP/.01, .01, .01, .6, .6, .6, .1, .1, .1, .50, .50, .50, /
DRY = DRAIN(1)
TMPS = DRAIN(2)
RDTYP = PAVE(1) + .01

IF (RDTYP = 2 ) 1, 2, 3

1 CONTINUE
C INITIAL EARTH ROAD CONDITIONS
DO 10 I = 1, 12
10 RCOND(I) = RCOE(I)
GO TO 9

2 CONTINUE
C INITIAL GRAVEL ROAD CONDITIONS
DO 11 I = 1, 12
11 RCOND(I) = RCOG(I)
GO TO 9

3 CONTINUE
DO 12 I = 1, 12
C INITIAL PAVED ROAD CONDITIONS
12 RCOND(I) = RCOP(I)
CONTINUE
RCOND(7) = DRY/12.
RCOND(8) = (12 - DRY - IMPS)/12.
RCOND(9) = IMPS/12.
RETURN
END
Appendix F

Review of Existing Maintenance Models

In the study of highway maintenance there is a wide variety of the type of models that may be useful. These range from general models of the complete road system designed to show in a general way the interaction of maintenance with other parts of the system, (10,12), to models designed to optimize the method of performing a particular maintenance operation (18,19).

In this review some of the existing maintenance cost predicting models will be discussed. These models are one of the major sources of information of the relationships between various parameters and their resulting maintenance needs. However, for use in a comprehensive transportation model to explore design, all of the existing models have serious shortcomings.

This is especially true if application over a wide range of geographical and social conditions is needed. All of the models have built in biases to better fit the conditions of the individual study area. This is a necessary adjustment if the model is to be valid. However, most of these biases are incorporated in the basic structure of the models and there is no provision to adjust them for use under changed conditions.

In the following sections several of the more interesting
models are reviewed briefly and their advantages and disadvantages discussed.

Highway Research Bulletin No. 155 (54): This bulletin describes two methods for estimating maintenance costs based on information available at the time of the report (1956).

The first method uses the factors of:

1. traffic volume
2. subgrade soil
3. thickness of surface
4. thickness of base and subbase

A "maintenance effort index number" can be selected for each of the factors from a provided scale. These are added and the sum used with a graph given in the report to find the expected cost.

This seems like a straightforward approach to the problem. However, no information has been found indicating that this model has ever been validated by comparing its predictions against actual maintenance costs. Other apparent shortcomings of this model are:

1. it is very insensitive to differences in traffic volume,

2. there is no provision for allowing for truck traffic,

3. there are no provisions for allowing for variation in climate, maintenance efficiency or maintenance standards,
4. maintenance cost is assumed to be proportional to area of surface (which may not be true for very narrow or very wide surfaces),
5. there is no way to allow for age of pavement.

The second method of estimating reported in this bulletin uses the parameter of:

1. physical condition of the surface,
2. surface width,
3. traffic volume,
4. surface type.

Numerical factors for each of these parameters are found and multiplied together to arrive at a "composite surface factor". This factor is then multiplied by a basic maintenance cost to find the expected maintenance cost. This work was done in Louisiana and has apparently been superceded by the work reported in Louisiana State Bulletin No. 85. This model is not suited to economic analysis since present surface condition is one of the controlling parameters.

Lago's Cost Model (11): The maintenance submodel used in this transportation model is based roughly on the concepts discussed in Bulletin No. 155 above. It uses a "basic maintenance cost" which is adjusted by the factors of pavement width and structural number (SN). Paradoxically this model predicts higher maintenance costs for thicker pavements. This is because the transportation model uses a pavement design
submodel to find SN as a function of traffic and CBR and the increased SN represents heavier traffic.

This model offers no way to evaluate different designs and ignores many of the parameters that apparently have a significant effect on maintenance costs. This model is typical of the lack of attention given to maintenance in many of the existing overall cost models.

Louisiana's State Bulletin No. 85 (28): This bulletin reports on the development of a model to predict the cost required to properly maintain portland cement concrete pavements in southern Louisiana. The model was found by weighted regression analysis and is: 

$$Y = 18,628.36 - 1,056.29X_1 - 926.07X_2 - 1,018.03X_3 + 233.43X_1X_2 + 21.56X_3^2$$

where $Y$ = cost in dollars to maintain adequately one mile

$X_1$ = subsoil factor

$X_2$ = surface condition

$X_3$ = surface width feet

This model apparently does a reliable job of predicting maintenance needs on the existing highway systems in southern Louisiana. However, the maintenance costs that were input into the regression program were estimated by local maintenance engineers. Therefore, in the final analysis any cost prediction estimated from the model is only what would have been estimated by the average engineer used in the study. These costs may or may not correspond to the actual maintenance
cost that should be spent.

Also the variables identified by the regression as important to maintenance cost only means that these are the variables considered by the engineers when they made their estimates. For instance if traffic volume and pavement design were not considered when the estimates were made they naturally will not appear in the final model.

Even if the model did not have the above shortcomings, the use of surface conditions as one of the input variables makes the model useless for economic analysis before construction. However, this is not a criticism of the report since this was not the purpose of the study.

1966 Louisiana Report (29): This report describes a study similar to the one above but for the prediction of maintenance costs on asphalt roads.

This study was based on actual maintenance cost data instead of on estimates. This procedure appears to be sound. However, the model developed by regression analysis had a coefficient of correlation of only 0.37 and is therefore not too useful in its present form for predicting maintenance costs.

Australian Models (12): This report presents two very simple models to predict maintenance costs for earth and gravel roads:

\[
\text{Earth Road Maintenance Cost} = 6E \\
\text{Gravel Road Maintenance Cost} = 150 + 3.7E
\]
where \( E \) is the average daily traffic. Although these models may do an adequate job of predicting maintenance under the local conditions for which they were developed, they probably ignore too many parameters to be generally valid for other locations.

The models developed for paved roads are more complex and represent one of the few attempts that approaches maintenance cost as a sum of several categories of work. Maintenance is divided into surface, roadside and shoulder maintenance. Three models are presented for various classes of bituminous concrete roads and two additional models are listed for surface sealed roads.

All of these models predict costs as a function of traffic volume and age. Although these models may predict maintenance costs in Australia very well they are too simplified to allow the investigation of tradeoffs between construction, maintenance and operating costs. The absence of parameters involving climate and soil also probably limits their use to locations that have conditions similar to the study area.

NCHRP Report No. 42 (27): This report presents a series of submodels for the various maintenance activities. These were developed by multiple linear regression analysis on massive amounts of data collected on the U.S. Interstate Highway System. These models help establish many of the relationships involved between physical parameters and maintenance cost.
These are useful for the prediction of the costs of maintenance activities other than surface repair which are usually not dealt with directly. This model helped establish some of the relationships used during development of the maintenance model described in Chapter 4.

Although this study provided useful information about various relationships, the models presented have several important limitations for use in an economic analysis. The most important are:

1. all the data was collected on multilane highways,
2. highways in the study were all fairly new and as a result surface maintenance was low,
3. all the studied highways had high type surfaces (no gravel, earth or surface treatment)
4. since pavements were designed as a function of traffic volume, these apparently cancelled out and no information was obtained about the effect of traffic volume and pavement design on surface maintenance.

NCHRP Report No. 63 (10): This report investigates the economic justification of standards for low volume roads. In order to make this analysis it was necessary to predict maintenance costs as a function of surface type, traffic type, and surface width. The authors concluded that insufficient data was available from maintenance records, highway needs studies and the literature to support maintenance prediction. As a
result these maintenance predictions are derived using engineering estimates based on a set of assumptions. The assumptions were based on gathered information and experience. The results of these derivations are presented in table form and appear to exhibit reasonable trends. However, many of the assumptions could of course be questioned and if different assumptions were used, a different set of tables would have resulted.

The tables presented were useful mainly as a check on the reasonableness of assumptions made and results obtained during this study.

Other Maintenance Models: Many other maintenance models have been developed. Most of these have been based on local experience and have no provision for adjustment for use under different geographical or social conditions (3, 66). Most of these are of the form:

\[ MC + A + B \text{ (Traffic Volume)} \]

These models are mainly of interest, where they are available to check the results of a more general maintenance model to insure that the results for the local situation are in a reasonable range.

In summary: several of the models reviewed furnished information about the relationships between various parameters and maintenance cost. Other models furnished ideas that were useful in developing the structure of the present maintenance model. However, none of the models reviewed are considered
suitable for realistically predicting maintenance costs under a variety of physical and social conditions.
APPENDIX G

POLYNOMIAL REGRESSION ANALYSES

As explained in Section 4.4.1, prediction of physical deterioration as a function of PSI is a necessary step in the prediction of maintenance cost. Data gathered during the AASHO Road Test was used to find the correlation between PSI and the three measures of physical deterioration found most significant during the road test, (SV, (C+P) and RD).

Polynomial regression analyses were made on the data from 73 road sections. The program used* for these analyses generates equations of successively increasing powers of the independent variable. As each higher degree equation is found the residual sum of squares is compared to the next lower degree equation. If the higher degree equation has not reduced this residual, the program stops. All the regression equations from linear through the one that gives the best correlation are printed out. The multiple-correlation coefficients and the F values are also computed and printed. Using this program, statistically significant equations were found to predict SV, (C+P) and RD as a function of PSI.

To find the correlation between SV and PSI, regression analysis was made on the variables of PSI and log (1 + SV). Log (1 + SV) was the transform of SV which gave the best

*IBM's program POLRG was used for these analyses (67).
correlations during the AASHO Road Test (32). The regression equation with the highest level of significance was:

\[
\log (1 + \text{SV}) = 0.031 \text{PSI}^2 - 0.54 \text{PSI} + 2.3
\]

This equation has a multiple correlation coefficient of .91. Using the F test the form of the above equation was found to be statistically significant at the 1% level. Solving this equation for \(\text{SV}\) yields:

\[
\text{SV} = \left[10^{0.031 \text{PSI}^2 - 0.54 \text{PSI} + 2.3}\right] - 1.0 \quad (4-15)
\]

Analysis of the AASHO data on \(\overline{RD}\) and PSI produced regression equations of low statistical significance. The best equation found had a multiple-correlation coefficient of .38. The F test indicated that the regression was not statistically significant at the 10 percent level. Examination of the source of the AASHO data revealed that there were two distinct groups of data within the 73 road sections studied. Most of the road sections sampled were on existing state highways, but 24 of the sections were on the experimental road test loops. Although these two types of roads had shown similar behavior as measured by slope variance, \(\overline{SV}\), the road test loops had deeper ruts at equivalent PSI values than the state highway sections. This could be easily seen on a plot of \(\overline{RD}\) vs. PSI for all 73 sections where the plotted points appeared as two distinct groups.

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Regression analyses were made on both groups of data. The best regression equation found for the state road sections was:

\[
\overline{RD}_s = -0.031 \text{ PSI}^2 + 0.09 \text{ PSI} + 0.32 \quad (4-16)
\]

This equation has a multiple-correlation coefficient of .61. The F test indicated that the form of the equation was statistically significant at the 10 percent level.

Regression analysis on the data from the 24 road sections of the actual test road yielded:

\[
\overline{RD}_h = -1.7 \text{ PSI}^3 + 0.56 \text{ PSI}^2 - 0.06 \text{ PSI} + 2.6
\]

The multiple-correlation coefficient for this equation is .92. The F test indicates that the form of the equation is significant at the 1.0 percent level.

The reason for the difference in the tendency to rut between the test loops and the state roads is not known. However, to obtain accelerated pavement deterioration, the loads on most of the test loops consisted exclusively of high volumes of heavy truck traffic. Most of the rutting was found to result from changes in the thickness of the paving layers (56). Since deformation of bituminous mixtures is time dependent this accelerated loading schedule with little time for deformation recovery may have contributed to the deeper ruts on these sections. It seems reasonable to expect that rutting tendencies of most roads may be closer to the behavior observed on the state road sections than to the
behavior of the specially loaded test loops. For this reason the regression equation found for rutting on the state road sections is used in the model.

The regression equation found for \((C+P)\) as a function of PSI was:

\[
(C+P) = (0.3 \text{ PSI}^3 - 1.3 \text{ PSI}^2 - 6.2 \text{ PSI} + 29)^2 \tag{4-17}
\]

The multiple-correlation coefficient is .68. The F test indicates that the form of the equation is significant at the 2.5 percent level.

All three of the regression equations found by regression analysis are statistically significant. The detailed results of this regression analyses are given in figure G-1.
<table>
<thead>
<tr>
<th>Parameters Computed by Program (65)</th>
<th>Values of Parameters for Independent Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\log(1+SV)$</td>
</tr>
<tr>
<td>No. of road sections in sample</td>
<td>73</td>
</tr>
<tr>
<td>Intercept</td>
<td>2.3</td>
</tr>
<tr>
<td>Coefficient of PSI</td>
<td>-0.54</td>
</tr>
<tr>
<td>Coefficient of PSI$^2$</td>
<td>0.031</td>
</tr>
<tr>
<td>Coefficient of PSI$^3$</td>
<td>---</td>
</tr>
<tr>
<td>Coefficient of PSI$^4$</td>
<td>---</td>
</tr>
<tr>
<td>Degrees of Freedom (due to regression)</td>
<td>2</td>
</tr>
<tr>
<td>Degrees of Freedom (about regression)</td>
<td>70</td>
</tr>
<tr>
<td>Multiple Correlation Coefficient</td>
<td>.91</td>
</tr>
<tr>
<td>F - Value</td>
<td>170</td>
</tr>
<tr>
<td>Percent level of significance (by F test)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Figure G-1:** Results of Polynominal Regression Analyses on AASHO Road Test Data
APPENDIX H

DESCRIPTION OF THE EXAMPLE PROJECTS USED IN THE STUDY

Model runs used as examples in this thesis were based on two actual projects. Information describing the projects was furnished by the International Bank for Reconstruction and Development. One project is located in Burundi in central Africa and the other is on the island of St. Lucia in the Caribbean Sea.

The project in Burundi is located in flat to rolling terrain with an average rainfall of 90 centimeters per year. The California Bearing Ratio of the subsoil is 12%. The proposed road is 5.5 meters wide with 1.5 meter shoulders. The road will have an average degree of curvature of two and an 8 percent maximum grade. The specific strategies simulated are described in the text for each example. Detailed description of the unit costs used for this project are given in Table H-1.

The project in St. Lucia is located in rolling and mountainous terrain with an average rainfall of 480 centimeters per year. The California Bearing Ratio of the soil is 10%. The proposed road is 7.3 meters wide with .9 meter shoulders. The road will have an average degree of curvature of 2.1 and a maximum grade of 8 percent.

In addition to the two projects described, a third project was made up by combining the physical description of
the Burundi project with appropriate unit costs for a location in the United States. The rainfall, soil and terrain described for the African project is typical of many locations in the U.S. and the type of road proposed is used in many rural U.S. areas.

Table H-1 lists the unit costs for labor, equipment and material used for the three projects.
<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Burundi</th>
<th>U.S.</th>
<th>St. Lucia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Distributer (self-propelled)</td>
<td>$/hour</td>
<td>4.00</td>
<td>3.00</td>
<td>1.25</td>
</tr>
<tr>
<td>Dump Truck (3 cu. m.)</td>
<td>$/hour</td>
<td>3.00</td>
<td>2.25</td>
<td>0.31</td>
</tr>
<tr>
<td>Tractor Loader (1 cu. m.)</td>
<td>$/hour</td>
<td>8.00</td>
<td>6.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Motorgrader (3.7 m. blade)</td>
<td>$/hour</td>
<td>8.00</td>
<td>6.00</td>
<td>2.50</td>
</tr>
<tr>
<td>Roller (self-propelled, ten ton)</td>
<td>$/hour</td>
<td>4.00</td>
<td>3.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Tractor with Mower (2.4 m.)</td>
<td>$/hour</td>
<td>2.00</td>
<td>1.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Water Truck (6 cu. m.)</td>
<td>$/hour</td>
<td>4.00</td>
<td>3.00</td>
<td>0.75</td>
</tr>
<tr>
<td>Labor (common)</td>
<td>$/hour</td>
<td>0.30</td>
<td>2.50</td>
<td>0.13</td>
</tr>
<tr>
<td>Equipment Operator</td>
<td>$/hour</td>
<td>0.50</td>
<td>3.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Foreman</td>
<td>$/hour</td>
<td>0.55</td>
<td>3.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Truck Driver</td>
<td>$/hour</td>
<td>0.42</td>
<td>2.80</td>
<td>0.38</td>
</tr>
<tr>
<td>Liquid Asphalt</td>
<td>$/liter</td>
<td>0.10</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Patching Mixture</td>
<td>$/ton</td>
<td>10.00</td>
<td>15.00</td>
<td>24.00</td>
</tr>
<tr>
<td>Cover Aggregate</td>
<td>$/ton</td>
<td>1.00</td>
<td>2.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Diesel Fuel</td>
<td>$/liter</td>
<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Gravel</td>
<td>$/ton</td>
<td>0.01</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>Gasoline</td>
<td>$/liter</td>
<td>0.13</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Water</td>
<td>$/m³</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table H-1: List of Unit Costs Used in Example Simulations