AIRFIELD PAVEMENT MAINTENANCE

by

BOBBY DAVID BARNES

SB, North Carolina State University

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Signature of Author ....
Department of Civil Engineering,

Certified by ....
Thesis Supervisor

Accepted by ....
Chairman, Departmental Commitee on Graduate Students of the
Department of Civil Engineering

ABSTRACT

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The demands for service placed upon airfield pavements is increasing at a substantial rate. The unexpected failure of these facilities may lead to air transport problems around the world. The prediction of airfield performance with time and the effects which specified maintenance programs may have upon this performance are important in the efficient operation of the facility.

In connection with any proposed pavement maintenance program two questions may be posed:

1. What is the best balance between initial construction cost and future maintenance cost; and
2. How much maintenance should be done on existing facilities?

No single answer to either of these questions can be applied to all airfield pavements. Instead each particular facility will operate under a solution which is satisfactory to its individual needs and resources.

To allow the facility planner or maintenance manager (i.e. decision maker) to answer these questions in the context of his own peculiar problems, an airfield pavement maintenance computer model has been developed which yields:

1. Estimates of the condition of the runway/taxiway pavement;
2. Estimates of the maintenance efforts required to change conditions;
3. Estimates of the associated costs with changes.

The maintenance model as presented in the thesis has been found, through sensitivity analysis, to validly predict performance trends under specified climatic and air traffic environments. While the model has not been fully calibrated, those areas which may prove most fruitful for further work are noted. The parameters of pavement thickness, traffic load (weight), subgrade support, and rut depth filled are identified as the most influential parameters.

While the model cannot "accurately" predict maintenance costs or pavement condition at this time, it should be able to do so with calibration. This process may be carried out either in a research or application atmosphere.

Thesis Supervisor: Professor Fred Moavenzadeh

Title: Associate Professor of Civil Engineering

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CHAPTER I

INTRODUCTION

1.1 DISCUSSION OF MAINTENANCE

The basic questions concerning maintenance of the airfield pavement are:

1. What is the best balance between initial system cost and future maintenance cost; and
2. How much maintenance should be done on existing systems?

The right amount or proper balance of maintenance for one facility may not be the same for another. For this reason a single answer which will be applicable at all airfields cannot be defined. However general methodologies and techniques by which the answer(s) to these questions can be determined for an individual facility are being sought by several agencies (National Aeronautics and Space Administration, U.S. Federal Aviation Administration, U.S. Army Corps of Engineers, Port of New York Authority, etc.). What is needed is a problematical approach for consideration of maintenance and its implementation via the development of an airfield pavement maintenance computer program.

This problematical approach should consider three entities: the facility suppliers, the facility, and the user. Conceptually the model should evaluate the existing or planned construction in the existing or predicted traffic and climatic environment. This evaluation would yield, first of all, expected physical damage or deterioration response with time. Secondly it should take the predicted damage quantities and estimate the effect they have upon the aircraft crew or passengers. This process should be capable of being repeated for each period the pavement is in service. Hence the proposed computer program should allow the simulated performance of maintenance during these periods and estimate both the cost of maintenance and the effect maintenance has upon the facility's performance.

1.2 GENERAL BACKGROUND

The observation has been made that the sudden loss of service on a runway at Kennedy International Airport in New York can tie up traffic patterns halfway around the world (1)*. A similar statement concerning service complications could be made about many of the other 21 air transport hubs** which are operating at or near capacity in the U.S. (2,3). These far-reaching and drastic effects are the result of continually increasing demands upon airfield service. These demands occur both in the number of passengers and in the number of aircraft (2-5). Accompanying this numeric growth of passengers and aircraft has come large increases in aircraft dimensions and weight (2-5). Increases of the type mentioned are not expected to cease in the near future (1970-1985) (6). Hence the runways of today and the future will be faced with functionally serving aircraft demands much different than those in the past.

In order to meet these growing air traffic demands two broad categories of solution exist:

1. Increase the number of present faciltíes;

   or

2. Increase the capacity of existing facilities (6).

The implementation of either of these categories will require knowledge of the performance properties of the facility. This knowledge is required to allow reasonable evaluation of the facility's condition such that sudden or unexpected losses of service may be unlikely to occur (7,8).

To this end it is desirable to be able to predict the state of performance of the runway pavement at any time, and the effect of any given maintenance program upon this performance.

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* Numbers in parenthesis refer to references.

** hubs - those airfields which handle 1% or more of the U.S.'s annual enplanements, e.g. O'Hare, Kennedy, L.A. International, etc.

Functionally, the airfield runway and taxiway pavements will be required to provide service to the user at an adequate level. This service may be perceived in two areas: 1. human systems and 2. mechanical systems.

1. The human system relates primarily to comfort and safety. This is to say that the passengers must be comfortable during ground movement; and the pilot must be able to execute movements in a safe manner.
2. The mechanical system deals with (a) the reliability of instrument readings, (b) the structural stability of the aircraft and (c) the condition of the cargo.

The task remains to evaluate how well the pavement meets the functional requirements of an adequate service level. In the evaluation of runways two groups are important: (a) the planners, designers, maintenance managers, and operators (suppliers) and (b) the users (8,9). Group (a) is generally interested in the deterioration or damage which the pavement undergoes while group (b) finds that the service which they receive from the facility is most important (10). In order for both evaluations to be made it seems feasible to formulate a model which predicts, first, damage (cracking, rutting, roughness) as a function of construction, traffic, and climate and second the effect this damage has upon the user's perception of service.

1.3 OBJECTIVES AND SCOPE

The objective of this thesis is to present a maintenance model which allows prediction of runway pavement condition and maintenance costs under specified maintenance programs. This model has been formulated as a computer program simulation.

This program is viewed as a tool which can aid the designer or maintenance manager in his decision-making process. In this respect the maintenance model allows tradeoffs between various maintenance policies and between initial construction and future maintenance to be rationally examined.

The presentation of the thesis is made in five chapters. Chapter II deals in detail with (a) the concepts of performance of constructed facilities and (b) the implications of a total cost framework for analysis. Tradeoffs between construction costs, maintenance costs, and user costs are examined.

Chapter III sets forth both the concepts and the detailed description of the maintenance model. Therein is pointed out the desirability of constructing a stochastic model to account for the random characteristics of traffic, of climatic environment, and of materials' properties. The later portion of Chapter III explains the deterioration, serviceability, roughness, and quantities and cost (material, labor, equipment) relationships used in the computer program. The empirical nature of these relationships is noted.

Chapter IV presents the results of sensitivity and tradeoff analysis conducted with the airfield pavement maintenance computer program. The presentation:

1. Examines the validity of the maintenance model response;
2. Isolates the input parameters and hence the computer program functions which have the most effect upon model response;
3. Delineates areas for most fruitful further research or calibration; and
4. Examines tradeoffs which may be investigated with the model.

The final chapter, Chapter V, presents a summary and evaluation of the present work together with recommendations for further work.

CHAPTER II

PERFORMANCE AND ECONOMIC CONSIDERATIONS

2.1 PERFORMANCE

In Chapter I the requirements for a functional airfield runway pavement were noted. Particularly it was stated that the facility should "provide service to the user at an adequate level". In other words the facility must meet serviceability demands. In addition this serviceability should be provided with a certain degree of reliability and an understanding of its maintainability. Collectively these three components, serviceability, reliability, and maintainability define the performance of a constructed facility. These terms and their implications will be explored in some detail below.

2.1.1 Serviceability

Success of any constructed facility requires that it provide service at some useful or adequate level. This in turn implies that the evaluation of the service provided by the facility lies with the user. Broadly defined, the term refers to direct, indirect, and subsidiary users (11).

As a group, all users can evaluate some of their reactions to the facility in terms of cost. Predominately the judgement of the indirect and subsidiary users are more influenced in this respect. However the direct user, passengers and crew, consider not only economic effects but also psychological effects (11,12,13). Psychological effects encompass perceptions or feelings of comfort and safety. Vibration and noise are most often cited in connection with these effects (9,14).

Serviceability is then a measure of how well the desires and needs (psychological, physical, and economical) of the users are met. In this respect no consideration is made for the future characteristics of the service. Serviceability implies only the existing or desired condition of the facility. Reliability and maintainability account for future states.

2.1.2 Reliability

Reliability accounts for the probability of the facility being in any one state at a particular time. That is, the probability that the facility can furnish the desired level of serviceability throughout some period of time; often referred to as a design life.

As an example consider two runways A and B. A has been designed for a traffic of 1000 coverages of aircraft having Equivalent Single Wheel Loads (ESWL) of 30,000 pounds. Whereas B was designed for the same ESWL's but for 2,000 coverages; i.e., construction effort or quality is higher for B than A. If we assume that the traffic and maintenance for each pavement is identical, reliability might be plotted as shown in Figure 2-1. Without making definitive statements concerning failure, it is apparent that as each runway accumulates traffic, the probability of failure increases.

Provided that the ultimate objective of each runway is to supply a pavement having a specific service level for 2,000 coverages, it is clear that the probability of A remaining at the desired serviceability level falls off more rapidly than does the probability of B. Hence, one sees that each runway provides service to the user but that the reliability of that service is different.

This example has shown a comparison of two differently designed runways under identical maintenance operations. An alternative to the provision of more construction effort lies in maintenance or maintainability considerations.

2.1.3 Maintainability

Maintainability may be defined as a measure of the effort required during the life of a facility to assure an adequate level of service. The manner in which this required effort is expended is termed maintenance. And, it may be divided into two categories, normal maintenance and corrective maintenance. Normal maintenance is of a preventive nature. Generally, it is composed of programmed activities which accomplish certain tasks at a given rate; e.g. sealing 75% of all cracks once a year. Corrective maintenance in contrast is an unscheduled activity. It is undertaken when a portion of the facility has failed or failure is impending; e.g. replacement of asphalt where a disabled aircraft has torn away a portion of the pavement.

In general, corrective maintenance cannot be accurately planned. Conceptually, more intense normal maintenance may or may not effect the potential need for corrective maintenance. Nonetheless, the proper planning and application of normal maintenance can effect system reliability. Consider the above example of runways A and B. The reliability of these two pavements could be made to approach each other under proper maintenance policies. That is, A could attain a higher reliability, if it were subjected to a more comprehensive maintenance policy. For example, if the maintenance policies had been;

A -	Patch	50% of all cracks
	Seal	40% of all cracks
	Fill	60% of depth of all ruts
B -	Patch	20% of all cracks
	Seal	10% of all cracks
	Fill	0% of depth of all ruts

then the corresponding reliabilities might approach each other, Figure 2-2.

Alternatively one could view A and B as having identical design and traffic, but with different maintenance policies, B more intensive than A. In this case Figure 2-1 could be viewed as a likely representation of reliability.

Another implication of Figure 2-1 concerns the relation between construction effort and maintainability. It is noted that A has lower reliability than B. Hence it may be recognized that in order to maintain the desired serviceability with a given reliability that more maintenance should be investigated for A.

At this point it should be clear that serviceability, reliability, and maintainability must be considered in the design process.

2.1.4 Performance of Constructed Facilities

Performance of a constructed facility is the embodiment of the three aforementioned components: serviceability, reliability, and maintainability. No system can effectively be evaluated without recognition of these either implicitly or explicitly. From a structural integrity view, performance lends itself fairly well to evaluation. On the other hand, from a user's psychological perspective the evaluation is much more difficult. As was mentioned earlier, vibration and noise effect the direct user, but to what extent this influences the users perceived utility is difficult to judge. Even more difficult to evaluate, is the relationship between the vibration level the user experiences and the structural integrity of the pavement. In order to begin this evaluation much work is needed in the fields of psycho-physics and pschometrics. The detailed examination of these fields and their implications is somewhat outside the realm of this thesis. (For a comprehensive explanation of this area see Thurstone (13), Fechner (15), Winkler (16), Galantner (17).) Nonetheless, the maintenance model deals with these areas in its evaluation and a brief discussion of them is presented in Chapter III.

In analysis and design of systems of constructed facilities, system performance and the economic costs of the facility must be evaluated. Most often the designer's task is to provide some level of performance within some set of cost constraints. Tradeoffs exist between construction cost, maintenance costs, and user cost. Hence it is economically feasible to evaluate the performance of a system within the context of a total cost analysis.

2.2 ECONOMICS

The planning, design, construction operation, and maintenance of any constructed facility must be considered within the context of a broadly defined environment. Four problem areas should be investigated: (a) economic, (b) social, (c) political, and (d) technical. One logical manner of attacking these problems is to ask a series of questions concerning the distribution of resources and the accruement of returns, Figure 2-3. It is assumed that the terms resources and returns may be considered in a broad sense economic but in a more specific sense social and political.

In this study, it is sought to provide the decision maker with a tool which will aid him in answering questions ⑤ and ⑥ of Figure 2-3. Consequently, some technique or methodology is required to allow evaluation of the costs involved: construction, maintenance, and user.

2.2.1 Total Cost of Service

Several alternative methods of economic analysis are available: (a) equivalent uniform net return, (b) net present value, (c) benefit/cost ratio, (d) equivalent uniform annual cost, and (e) internal rate of return (for a thorough treatment of these see Samuelson (12), Baumol (18), Grant and Ireson (19), or Winfrey (20). The method proposed for evaluation of costs in this study is present value of total costs.

Present value of total costs is a particularly attractive method in that it allows not only the evaluation of construction costs, maintenance costs, and users' costs; but it also provides the decision maker with a time stream flow of resources - costs. This last aspect may be of substantial importance in that it allows consideration of expenditures of future resources as balanced against projected availability of these resources. It is evident that the benefits of the total cost technique are lost if any of the components of cost are deleted or misjudged. In previous years the components, construction cost, and user cost have received much attention. Consequently, several sophisticated techniques exist which allow close approximations of their values. (See Manheim, et. al. (21)). Contrastingly, the estimates of maintenance cost, when not omitted entirely, have relied on what can only be termed "experience". Several objections to these estimates exist. Two of these are:

1. The facility for which the estimate is rendered must already exist in

order for experience to be gained.

2. In order for estimates to be made for a proposed facility, a similar facility must exist in a similar environment.

Of course several other objections concerning changing traffic and changing maintenance policies exist. Consequently an accurate mechanism for maintenance estimation will be desired.

2.2.2 Details of Total Cost Evaluation

The formula used for the evaluation of present worth of total cost is:

$$TC_i = \sum_{j=o}^{j=n} \frac{CC_{ij} + MC_{ij} + UC_{ij}}{(1+d)^j} \tag{2-1}$$

where TC_i = Present worth of strategy i over an analysis period of j years

CC_{ij}, MC_{ij}, and UC_{ij} = respectively construction, maintenance, and user costs predicted for strategy i in year j.

d = discount rate or the opportunity cost of capital

By this method, the strategy with the lowest present worth of total service cost is preferred (22). Hypothetically, this technique could be expanded to include costs associated with political and social effects. However this does not appear practical. Nevertheless the total cost approach can yield costs for the facility which are required in the evaluation and comparison of different projects within a broad framework.

From the total costs perspective the components of maintenance costs and user's cost do not necessarily remain equal for two different construction efforts. (It is assumed that more construction effort requires increased construction costs.) In fact many combinations of construction costs, maintenance costs, and user costs are possible. It was shown in the preceding section concerning performance that combinations of maintenance and construction effort may result in facilities which have equal reliability. Furthermore, it can be shown that these components effect the serviceability of the facility. In this respect it should be recognized that interaction among the cost components is not independent. Hence this leaves the way clear for consideration of tradeoffs among the three.

2.2.3 Maintenance-Construction Costs

Intuitively, one may assume that low maintenance costs are associated with high construction quality. Conversely, high maintenance expenditures should be required for projects having low construction quality. These maintenance-construction relations are most nearly true for projects which must meet similar serviceability requirements within equivalent economic environments. Figure 2-4 shows a relationship between two projects which must meet similar serviceability requirements with time. Apparently the low quality construction could have approached the serviceability history of the high quality construction if more maintenance effort had been expended. Furthermore, it could be shown that the service life of X could have approached that of Y had a smaller maintenance effort been expended on X.

On examining the effects of different maintenance efforts for projects having equal construction quality, Figure 2-5, it can be seen that the serviceability histories of A and B are considerably different. By relating ΔS_1, ΔS_2 (change in serviceability - improvements) and M_1, M_2 (maintenance effort), a maintenance cost-improvement relation can be proposed similar to Figure 2-6. For this relationship it is assumed that a higher maintenance effort ($M_1 > M_2$) regains a larger value of serviceability ($\Delta S_1 > \Delta S_2$). Presumably M_1 is more expensive than M_2.

It should be noted that the relationship of Figure 2-6 is valid for only one time period. Even though later time periods will require ΔS_x improvements equivalent to previous ΔS's, the cost will not necessarily be the same. This difference is related to the method of achieving a specific ΔS_x through a maintenance effort M_x, i.e., $M_t \neq M_{t-1} \neq M_{t+1}$ even though $\Delta S_t = \Delta S_{t-1} = \Delta S_{t+1}$ because the maintenance operations for M_t, M_{t-1}, and M_{t+1} may be entirely different. Consequently, the associated costs of repair will be different. Hence, the representation of the relationship between maintenance effort and improvement requires a family of curves as shown in Figure 2-7.

If one wishes to also associate maintenance effort and improvement with construction quality, another family of curves will be needed as shown in Figure 2-8.

The foregoing serviceability, construction quality, maintenance effort interactions show some of the complexity involved in designing, constructing, and maintaining constructed facilities. These interactions have special significance for runway pavements because they allow the designer or maintenance manager the alternative of meeting service level requirements in several different ways.

2.2.4 User Costs

The maintenance-construction tradeoffs discussed above concern themselves with equivalent serviceabilities. That is, there are combinations of construction effort and maintenance effort which can provide similar serviceability histories (performance). In this respect the user will experience no change in his cost. However, if the service level differs from strategy to strategy the user's cost will vary. Explicity this means that no trouble occurs when using present value of total costs for comparing projects of similar performance.

In contrast, modifications must be made if the service level varies. Implicitly, varying levels of service are accompanied by changes in user costs. And unless the facility is subject to an inelastic demand for service, the number of users will change. To some extent, large metropolitan airfields represent facilities having an inelastic demand for service. Whether the runways are in poor condition or excellent condition, the same number of aircraft will seek to land. This observation is made under the influence of present capacity operations at many of this nations air transport hubs. There exists the probability however, that the inelasticity of this demand cannot be extrapolated into future years. Prediction concerning demand must consider that new airfields are under construction (and existing fields are undergoing reconstruction) and will enter the air transport market in a competitive manner. Furthermore, it is evident that the inelasticity of the demand has limits, i.e. after a certain user cost is passed other modes of transport will become more popular and more competitive. Therefore the decision maker must have some methodology for establishing service levels and thereby user costs.

A modification of equation 2-1 will allow consideration of various service levels together with maintenance and construction costs under changing demands. It is suggested that the concept of <u>willingness to pay</u> be used in the modification of the present worth of total costs technique.

A thorough treatment of this evaluation is not essential here. Thus the reader is referred to reference (20) for a more detailed description.

2.3 SUMMARY

For a given level of serviceability there exist many combinations of maintenance and construction effort which will provide the desired performance. For each combination considered there are costs associated with construction and maintenance. It has been shown in section 2.2.3 that maintenance costs and maintenance efforts vary with construction quality. In fact even though the same change in serviceability may be desired for two different projects or at two different times the maintenance model computer program which is described in the next chapter allows tradeoffs between construction and maintenance to be examined in terms of service, damage, and maintenance costs. While the model does not allow the specification of ΔS's it does allow the evaluation of the resulting costs and performance under specified maintenance efforts, M's. This means that those relationships that are discussed in section 2.2.3 have been established, but in reverse of the manner described therein (i.e. M's are specified and ΔS's are evaluated and output in combination with the service level after maintenance).

The concept of a total cost evaluation has been introduced to show how different combinations of construction and of maintenance may be evaluated by the decision maker (i.e. planner, designer, maintenance manager, operator). The third component, user costs, should have no significant effect upon the total cost decision unless changing levels of service are to be considered. The actual evaluation of user cost is not a part of this study. However it has been discussed because it forms an integral part of the proposed economic evaluation technique; and hence must be considered in any meaningful economic evaluation.

It should be apparent now that the intent of this study is not to formulate a decision making model. Instead the purpose of this study is to present both in concept and in detail a tool which can aid the decision maker in his task. This tool should be able to predict costs and performance which will allow decisions to be made more effectively within a broad environment involving not just technology and climate but also politics, economics, and society.

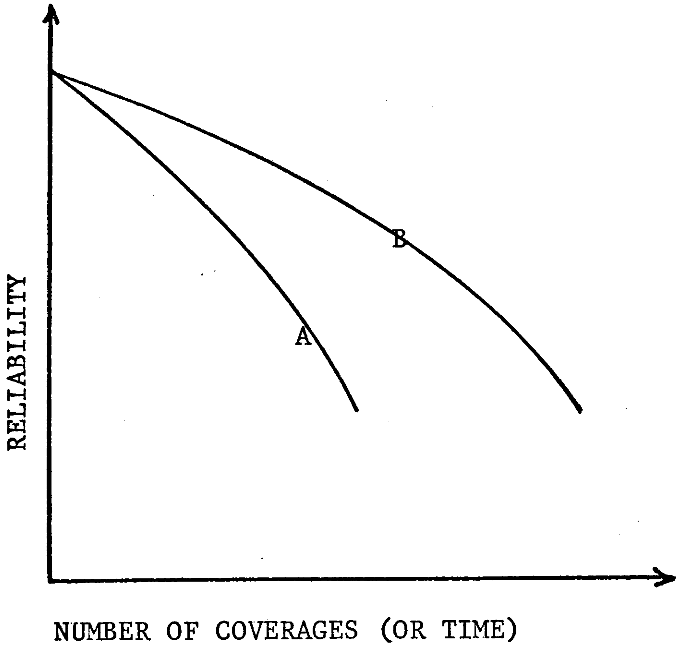

Figure 2-1: Reliability Of Two Different Runway Designs Under Identical Traffic And Maintenance

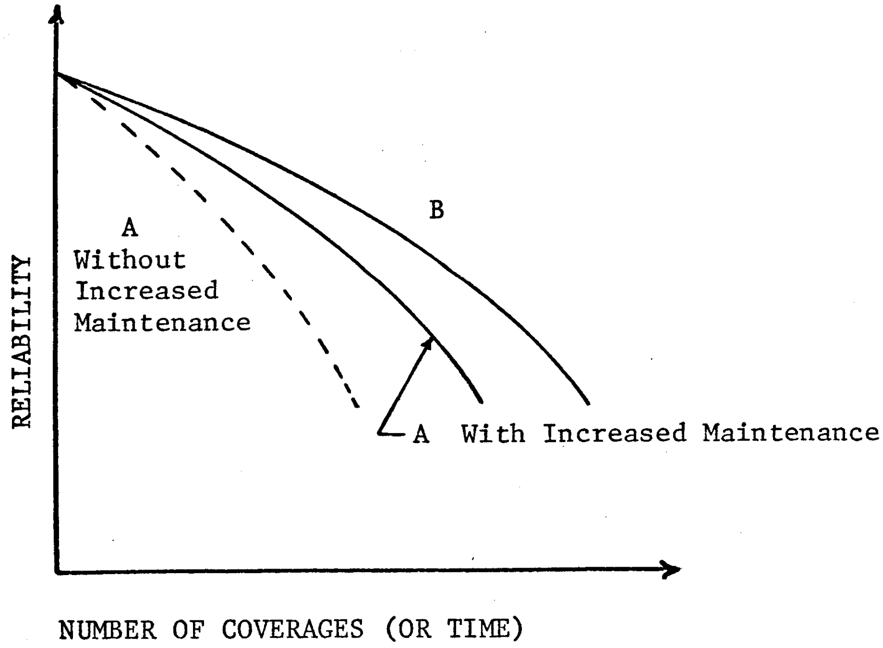

Figure 2-2: Reliability Under Different Maintenance Policies A More Intensive Than In Figure 2-1

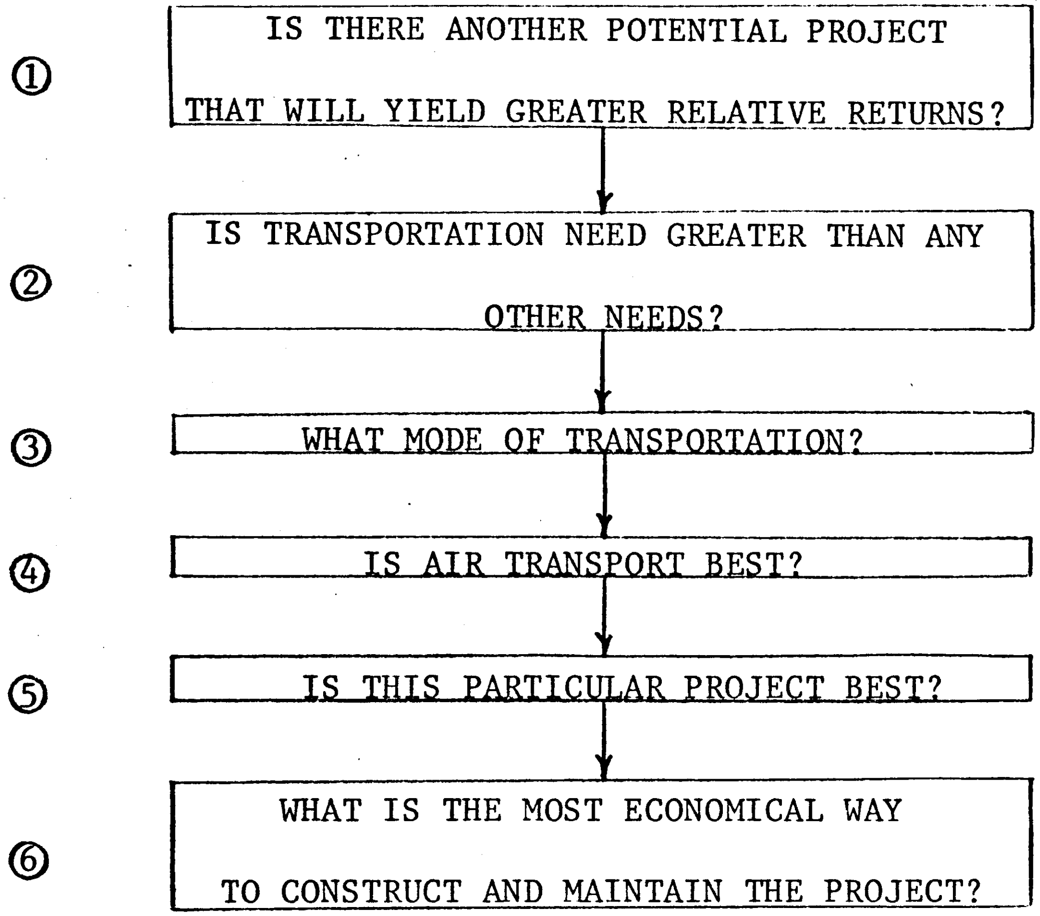

Figure 2-3: Sequence Of Questions To Be Asked In The Allotment Of Resources

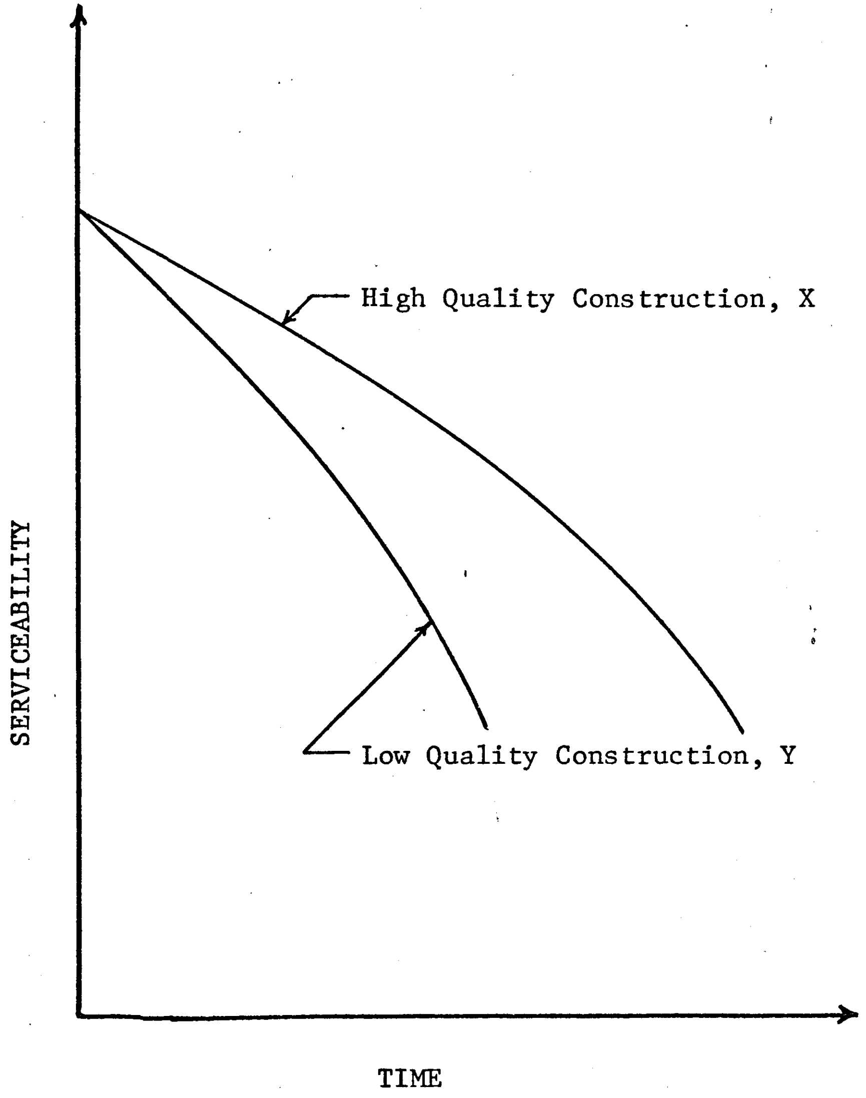

Figure 2-4: Serviceability Of Different Quality Construction (Maintenance effort and loading history equal)

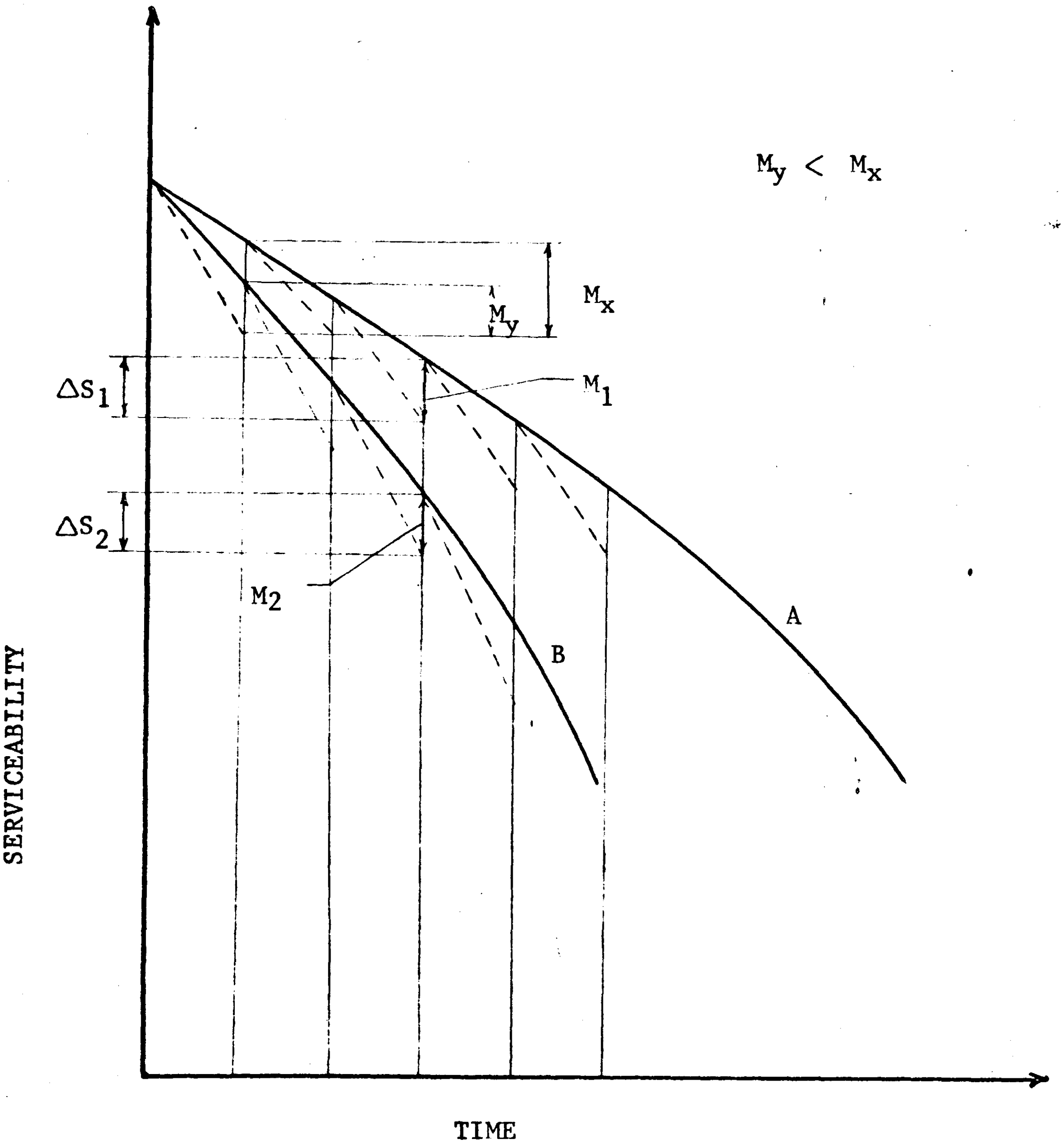

Figure 2-5: Serviceability - Time Relation For Equal Initial Construction Quality (Equivalent loading history but different maintenance effort)

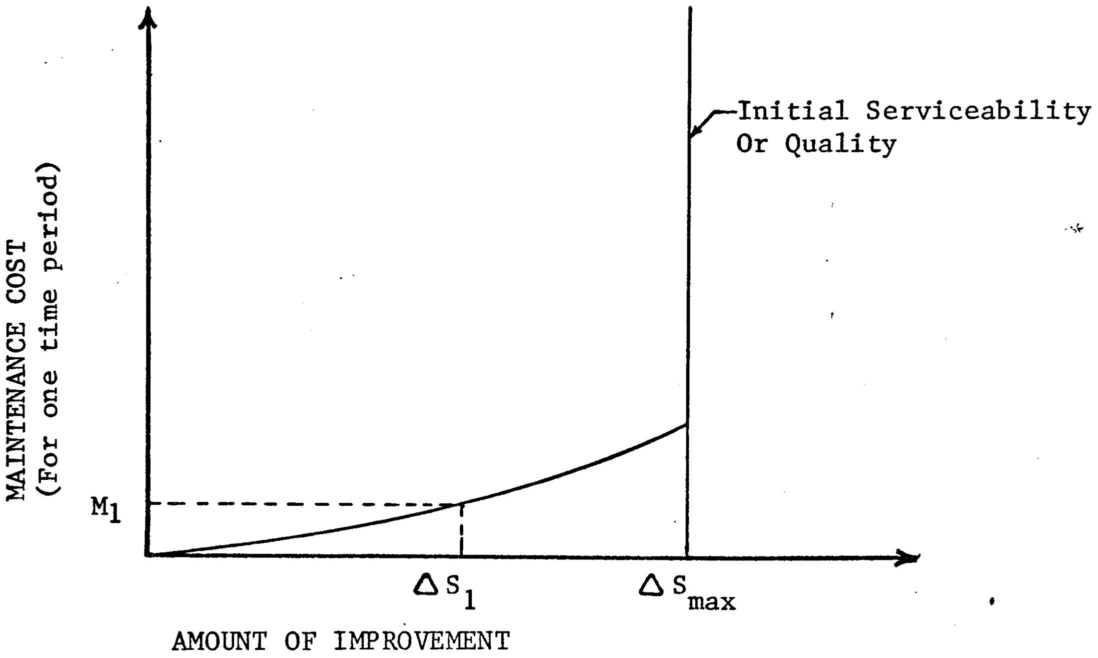

Figure 2-6: Maintenance Cost - Improvement Relation (ΔS denotes increment of improvement)

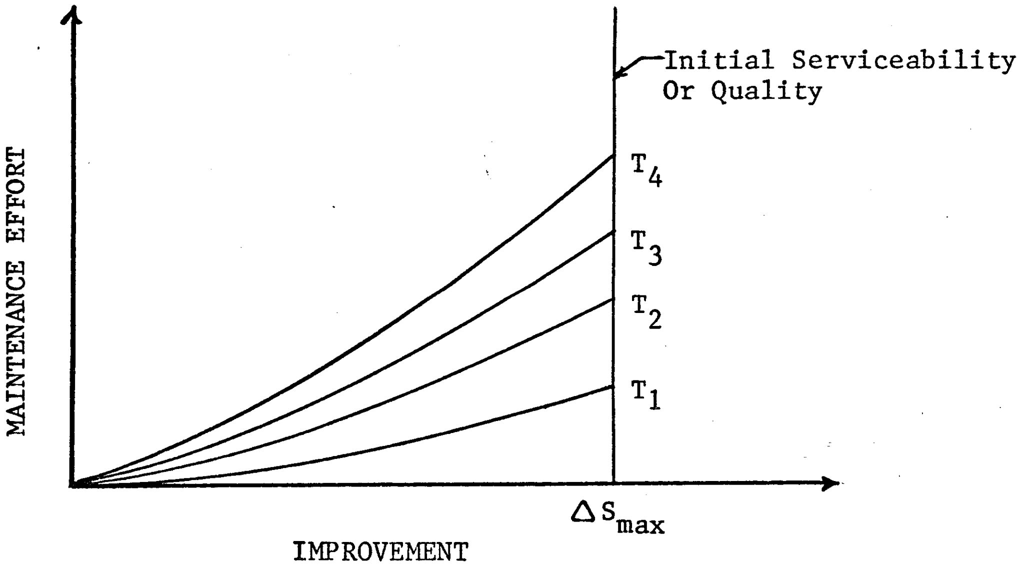

Figure 2-7: Maintenance Effort - Improvement Changes With Time, T_i. (Relationship assumes equivalent loading and initial quality of construction)

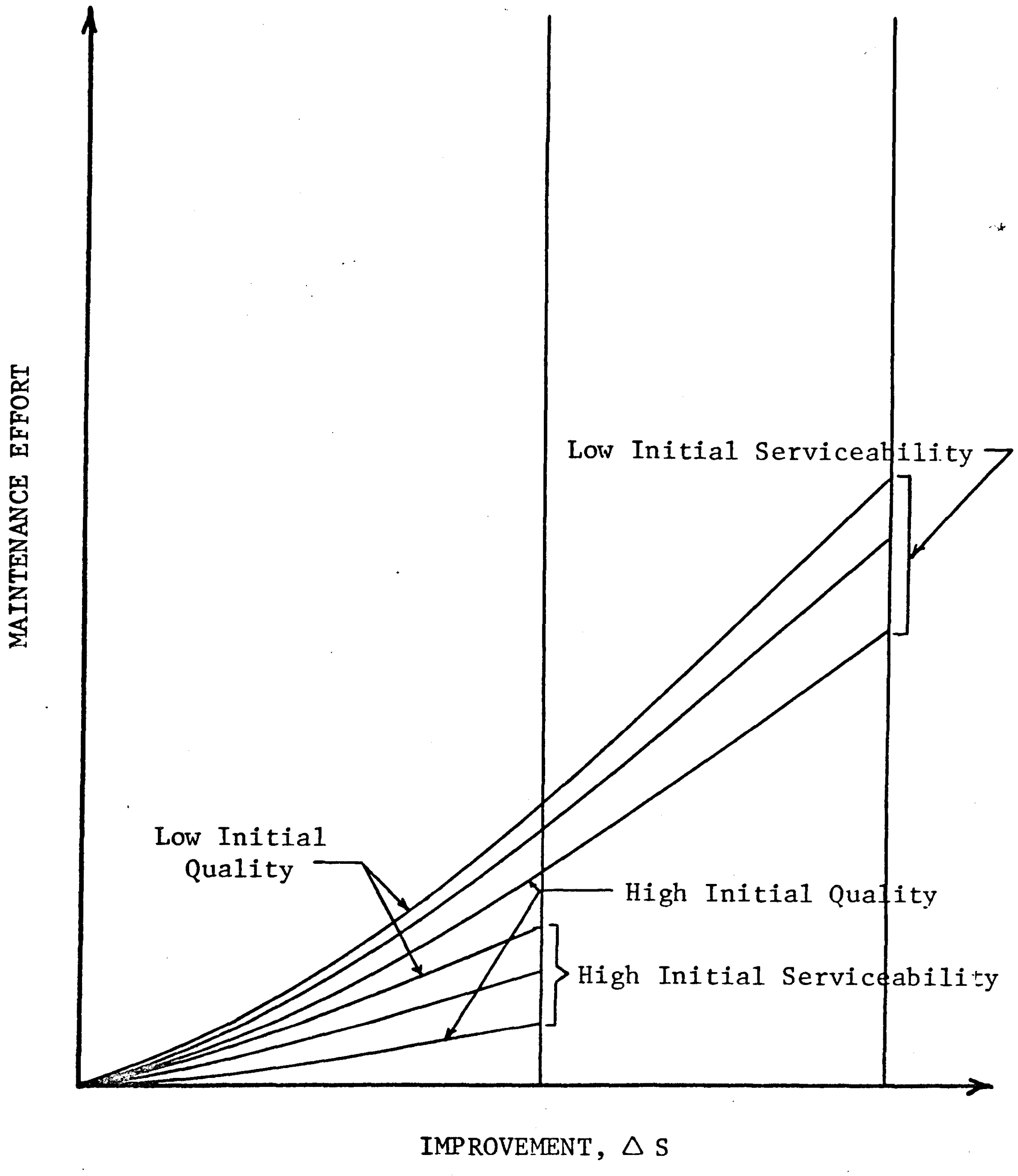

Figure 2-8: Maintenance - Improvement With Varied Maintenance Effort And Initial Construction Quality

CHAPTER III

THE MAINTENANCE MODEL

The maintenance model described in this chapter forms the central portion of this thesis. The chapter is divided into two sections. Section 3.1 deals with the model concept. It notes both the need for stochastic modeling as well as the empirical nature of the current model. The detailed description of the airfield pavement maintenance model follows in section 3.2. This section discusses the relations which were chosen for simulating pavement deterioration and maintenance and their operation. The operation of the model is explained by the use of an example.

3.1 MODEL CONCEPT

The driving motivation for maintenance operations is to maintain adequate serviceability at a desired level of reliability. In the model concept developed herein, serviceability, reliability, and maintainability are not input parameters. Rather, the model evaluates proposed or existing designs in a specified climate and traffic environment and yields indications of these performance parameters. These indications take the form of estimates;

1. Estimates of the condition of the runway/taxiway pavement;
2. Estimates of the maintenance efforts required to change conditions;
3. Estimates of the associated costs with changes.

Ideally the performance of the pavement could be shown as Figure 3-1. The performance, P, as shown can be related to damage, D, in the pavement. If P and D are fractional quantities and hence range in value between 1.0 and 0.0 inclusive, a relationship between them may be established as a function of time or traffic.

$$P(t) = 1 - D(t) \qquad (3\text{-}1)$$

where t = traffic or time
at t = 0.0, P = 1.0
and at P = 0.0, t = time at end of service
life, D = 1.0

This is the concept upon which this work is based.

3.1.1 Ideal Structural Concept of Model

In concept the model should evaluate the existing or planned airfield pavement construction and yield estimates of its performance. From the point of view of the supplier (planner, designer, operator, maintenance manager, etc.,) and user the amount of damage or deterioration and the level of serviceability are important. Hence it appears that the complete evaluation of this constructed facility may require at least two transfer functions, T and U. Where T (Y_i) relates some set of structural design properties, Y_i's, to the future pavement response (damage or deterioration) which the facility will exhibit under a predicted climatic and traffic environment. Once this response is predicted the $U(X_i)$ function evaluates the damage or deterioration measures, X_i's, and predicts the reaction of the user. Parameters in the Y_i set include materials properties, pavement geometry, climate, and traffic. While the X_i set may be composed of such damage characteristics as cracks, ruts, and roughness. This is the technique which is proposed in the ideal and current model. At first a deterministic solution of T and U seems applicable, however a stochastic approach is more reasonable (23).

The stochastic approach is preferred due to the probabilistic nature of the pavement and user responses. It should be noted that the observed response (damage) of the pavement structure depends upon the probabilistic nature of loading rate effects (24, 25), the position and magnitude of the applied load (26), climate (27), materials type (26), previous traffic history (26), temperature (26), and construction variables (28). Furthermore the perceived utility of the users will also exhibit some mean value together with a distribution of perceptions.

The ultimate objective of the pavement facility is to provide service to the user. The interim objective of this study is to yield estimates of maintenance cost and the associated maintainability and reliability. To associate these objectives with the desired results and format of a model, an ideal strategy must be formulated. First it is desirable to break the problem into its component parts. These parts include input, damage evaluation, aircraft response, and user response. This division implies a linear structure in which each successive component of the system responds to the preceding component. In the simulation model this simply means that responses are calculated step by step. The generalized ideal model might operate as follows:

a. Input pavement design parameters
b. predicted climatic environment
c. predicted traffic
d. response characteristics of aircraft
e. response characteristic of users
f. calculate damage response of pavement from traffic and climate
g. response of aircraft to runway
h. response of user to aircraft

Superimposed on this process are maintenance activities and maintenance cost routines. In flow chart form the total process might appear as Figure 3-2.

Recall that it is most desirable to investigate stochastic modeling for this system. This implies that a certain knowledge of system variables exists. The knowledge should include not only material properties but their accompanying distributions for the pavement system. For the user the response character of cargo would be needed as well as the response character of passengers and crew. These relations require not only a great deal of data but also a reasonable understanding of how the components of the system interact.

At the first level of interest, the pavement, it has been pointed out that many factors effect its structural response and/or damage. Elliot (29) has made the following observation: "... the indicators of structural inadequacy are the manisfestations of the physical failure of the facility, in the particular load, temperature and material property environment. It is therefore pertinent to ask whether analytical models, mathematical or otherwise could be found to account for the manner in which a particular load-temperature-material property-environment would effect the performance of the layered structure." The author of the present thesis knows of no such all inclusive model in operational existence at the present time (1971). Likewise models for aircraft response and user response are required. One model by Tung, Penzien, and Horonjeff has particular promise for predicting airframe responses (30). Furthermore a model by Coermann (31) may be used to predict the physical response of human users in the aircraft. The most well developed model is the aircraft response model while the user model is perhaps the least developed. Obviously the user response is a difficult evaluation in that physical and pschological models are required.

Even though many problems are apparent a rational simulation and evaluation of the responses of the several system components may be proposed within the ideal framework of Figure 3-2. Three submodels are required (a) pavement, (b) aircraft, and (c) user. In connection with each of these the author has found three models which may, after much work, be combined as a total rational model. Ashton (32), Elliot (33), Findakly (34), and Soussou (35), have all worked on stochastic models of the viscoelastic nature of bituminous pavements. The work to date has not resulted in a final damage model but it promises to in the near future. The aforementioned model by Tung et. al. (30) has much promise. It is formulated as a deterministic model. Response of the airframe in terms of vibrations and acceleration may be predicted. The third model needed is one which simulates user response. Assuming that human response is most critical (i.e. cargo response can be altered by packing techniques) the model of the human body by Coermann (31) may be used. This model presently has the limited capability of predicting average physical responses. By a thorough investigation of human response to motion (vibration and acceleration), the fields of psychology and human factors might be used to derive a rational user response function. At the outset of this study none of the three models mentioned were in suitable form for incorporation. However the rationale which surrounds these has been thoroughly investigated and where appropriate utilized. Hence due to the present shortcomings of the above an empirical technique is used.

3.1.2 Current Model

The current model is not viewed as a completed study but as an interim tool. In its present form it should be able to aid two groups (a) researchers and (b) designers and maintenance managers. With some additional work in the area of comparison and calibration, it is thought that the model, as it exists, may be used as a tool for the designer and maintenance manager in the area of service life prediction and maintenance planning. The researcher should find the interactions which occur in the model instructive and helpful.

3.1.3 Basic Relationships

Before dealing in detail with each component of the program, the essential relationships between pavement, aircraft and user should be presented. The predominant pavement factor of interest is macro-roughness or surface unevenness (14, 36-44)*. Pavement roughness, defined as deviation from a smooth flat horizontal surface, causes several modes of movement or vibration, vertical, horizontal, and angular, in the airframe (30, 42, 44). These vibrations together with their amplitude have been shown through human factors research (14,36,37) to effect the users perception of comfort and/or safety. Therefore the two parameters which this study is most interested in are roughness and vibration.

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*Macro-roughness does not include skid resistance problems which are of a smaller scale and termed micro-roughness. For a thorough review of skid problems and their possible solution see Dahir (45).

3.1.4 Performance Concept

The components serviceability, reliability, and maintainability may be examined with the model. Measures of service are derived by investigating the vertical acceleration to which the passenger is subjected. Maintainability may be inspected through the service level-time relationship which results with changes in maintenance policy. And reliability can be checked by comparing the service behavior of the facility under equal traffic and environment but with different maintenance and construction strategies (see section 2.1.2).

It should be recognized that with these capabilities the model not only approaches the ideal concepts but that it becomes a useful tool to those experienced in airfield maintenance.

3.2 DETAILED DESCRIPTION OF MAINTENANCE MODEL

The preceding section, 3.1, has shown that the maintenance model is based upon the concept that damage and performance are related. This implies that if one can be predicted the other can be determined. In section 3.1.1 it has been pointed out that it is desirable to determine some functions T and U which allow first the prediction of damage (as a function of materials properties, pavement geometry, climate, and traffic) and secondly the prediction of user response. Relationships which allow these determinations are formulated in the current model. These relationships have been used in programming an airfield pavement maintenance computer simulation using the Fortran IV computer language (46). Basically the computer program performs four functions:

1. Simulates deterioration of the pavement by predicting the change in roughness as a function of traffic and environment.
2. Predicts changes in serviceability with changes in roughness.
3. Estimates changes in roughness as a function of maintenance policy.

4. Estimates quantities of labor and material and costs for a specified maintenance policy.

The structure of these functions within the program is presented in Figure 3-3.

Each of the four individual functions are described in detail within this chapter. Furthermore, at the end there is included a brief summary of the required input and expected output of the program.

3.2.1 Deterioration

The primary value to be considered in deterioration is surface roughness. It has been shown that roughness may vary linearly with both the weight and number of applications of traffic (47,48,49). Nevertheless one realizes that an aircraft having a weight of 100,000 pounds per landing gear effects this deterioration of the pavement differently than one having 30,000 pounds per gear. The approach used in this study concerns the equating of some common measure of traffic to a measure of damage (50-54). Therefore derivation of equivalence factors which allow the reduction of several different loading conditions to a common denominator is desirable. The Corps of Engineers pavement design method has been used in the derivation of these equivalence factors (55-59).

Considerations for pavement properties and traffic may be represented by (47,55,60,62):

1. Subgrade support
2. Equivalent pavement thickness (60)
3. Equivalent coverages*

The Corps of Engineers' thickness design equation allows the investigation of the interaction of these parameters.

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*"a coverage occurs when each point on the pavement surface has been subjected to one maximum stress by the operating aircraft" (61).

$$t = (0.23 \log C + 0.15)\sqrt{\frac{P}{8.1\ \text{CBR}} - \frac{P}{p_c}} \qquad (3\text{-}2)$$

where: t = thickness of flexible pavement structure

C = traffic volume, (coverages)

P = wheel load, (single or equivalent single wheel load, ESWL - pounds

CBR = soil strength measurement, (California Bearing Ratio)

p_c = tire inflation pressure, (psi).

Equation 3-2 may be rewritten in terms of coverages:

$$C = 10^w \qquad (3\text{-}3)$$

$$\text{where } w = \left\{\left[\frac{t}{\frac{P}{8.1\ \text{CBR}} - \frac{P}{p_c}} - 0.15\right] \frac{1}{0.23}\right\}$$

With equation 3-3 equivalent coverages may be determined via equivalence factors, EF, as derived in equation 3-4 and shown schematically in Figure 3-4.

$$EF = \frac{C_{ta}}{C_x} \qquad (3\text{-}4)$$

Where:

EF = Equivalence factor

C_{ta} = Coverages to failure for the aircraft for which the pavement was designed

C_x = Coverages to failure for any aircraft, x other than the type for which the runway was designed.

To account for climatic influence, subgrade support during the spring thaw period was considered. An environmental factor, ENVFT, was derived from Asphalt Institute (62) and Road Test Research (63).

$$\text{ENVFT} = \frac{\log_{10} \text{CBR}_{\text{design}}}{\log_{10} \text{CBR}_{\text{spring}}} \qquad (3\text{-}5)$$

Both the equivalence factor, EF, and the environmental factor, ENVFT, are used to determine the total number of equivalent coverages per year (see Figure 3-4).

The following example best explains the equivalent loading calculations.

EXAMPLE

Given

Type Aircraft	Number of Coverages/Year	Equivalent Single Wheel Load* (kg.)	Tire Inflation Pressure (kg/cm^2)
1	100	28636	10.6
2	100	30909	11.6
3	100	30909	11.6
4	100	15909	9.2
5	100	18181	10.2
6	100	41818	12.7

Pavement Thickness = 71cm.
Design CBR = 10.0
Spring CBR = 7.0

*Determined by Corps of Engineers Method (56,57).

Findings For Loading Only

Type (I)	Coverages to Failure CFAIL(I)	Equivalence Factors	Equivalent Coverages For Year
1	13,954	1.0	100
2	8,354	1.67	167
3	8,354	1.67	167
4	774,284	0.018	1.8
5	247,691	0.056	5.6
6	1,780	7.84	784

Total For Year = 1, (TOTAC) = 1225 coverages

Determine Total, With Environmental Factor

Given 1. SPTHW, % of traffic during spring thaw period

SOLUTION 1. Determine number of equivalent coverages during spring thaw, SPRNG

SPRNG = Total For Year, (TOTAC) x SPTHW

2. Determine ENVFT, Environmental Factor

$$\text{ENVFT} = \frac{\log_{10} \text{DESIGN CBR}}{\log_{10} \text{SPRING CBR}}$$

$$= \frac{\log_{10} 10}{\log_{10} 7} = 1.18$$

3. Determine total corrected equivalent loadings for year, YTOTL

YTOTL = (TOTAC - SPRNG) + (SPRNG X ENVFT)

YTOTL = 1270 Coverages

The next step after calculating the equivalent loadings for the year involves determining the amount of associated roughness. As was previously noted the deterioration-loading relation can be represented as a linear process. This of course implies that a sharp increase in traffic will be accompanied by a similar rise in roughness.

All the traffic in the example has been converted to equivalent coverages of aircraft type 1, CFAIL(1). Thus the change in roughness, RCHNG, for the example may be determined.

$$\text{RCHNG} = (\text{YTOTL}/\text{CFAIL}(1)) \times 158\text{cm/km} \qquad (3\text{-}6)$$

where:

RCHNG = change in roughness, cm/km

158 = range of roughness variation in cm/km

New construction = roughness = 79 cm/km

Failed condition = roughness = 237 cm/km. (64)

YTOTL = Total environmentally corrected equivalent coverages for year, equal to 1270 for the example

CFAIL(1) = coverages to failure of aircraft type 1, equal to 13954 coverages in the example

Therefore RCHNG for one year is

$$\text{RCHNG} = (1270/13954) \times 158 = 14.38 \text{ cm/km.}$$

Hence the roughness at the end of year 1, before maintenance is:

$$\text{Roughness} = 79.0 + 14.38 = 93.38 \text{ cm/km}$$

The reader should refer to the flow diagram of the current model Figure 3-3. From here it can be seen that the foregoing process can be repeated in part or in full for each year of analysis.

3.2.2 Serviceability-Roughness

Work by Hutchinson (14), Goldman (36), and Parks (37), and others leads to the concept of roughness related serviceability. It is seen from much of the work done by NASA (65), ALPA (66), and the U.S. Corps of Engineers (67) that pavement roughness directly effects vibration of both the human and mechanical systems which traverse the runway/taxiway. Vertical vibration is considered the most critical case.

Human response to vertical vibration may be characterized as shown in Figure 3-5. The range of frequencies from 0 cps to 20 cps is particularly critical because man's natural capacity for vibration absorption is least effective in this range (14). For this first model a serviceability relation is formulated by investigating vertical acceleration (VA) in the 5 cps range.

Establishment of an arbitrary measure of serviceability, as in the AASHO Road Test, (63), may tend to limit the utility of the model. Consequently, the model predicts and evaluates vertical acceleration, VA, as a function of roughness. This procedure is more generally useful in that it will allow consideration of the pavement serviceability to the airframe, cargo, instruments, crew, and passengers. In these early stages of development the model is used to evaluate serviceability in relation to human response. Since the major concern at this stage is service to the passengers and crew; a safety criterion was chosen in connection with failure. The failure state is defined as that condition at which the VA $\geqq$ 0.7g because it becomes extremely difficult for the pilot to carry out his duties safely at this amplitude of vibration (especially in the 5 cps to 20 cps range of interest in this study) (14,40).

The shape of the acceleration-roughness deterioration curve (Figure 3-6B) may be determined by considering a variety of runway profiles with their accompanying roughness and acceleration measures. Actual comparison of runway roughness and resulting vertical acceleration has not been undertaken in this study. Rather the relationship has been assumed. It is noted that normal bituminous pavements vary from a roughness of 50 inches/mile (79 cm/km) to 150 inches/mile (237 cm/km) from their newly constructed to their failed states respectively (64). Equation (3-7) is the result of associating 0.1g and 1.0g vertical acceleration with these roughness measures and assuming a linear relationship for intermediate values (see Figure 3-6C).

$$VA = -0.35 + 0.0057\ R^{**} \qquad (3\text{-}7)$$

where:

VA = vertical acceleration in g's

R = roughness in cm/km.

The foregoing allows two relations to be considered:

1. effect of number of equivalent coverages and climate on roughness; and
2. effect of roughness on vertical acceleration.

3.2.3 Maintenance-Roughness

As roughness changes so do the associated modes of deterioration; rutting and cracking. With the aid of Road Test damage data (63,67) and regression analysis (68), the form of equations 3-8 and 3-9 has been determined.

$$CP = 627.9 + 89\ \sqrt{0.633\ R}^{**} \qquad (3\text{-}8)$$

$$RD = -26.7 + 0.338\ R + 0.335\ \sqrt{CP}^{**} \qquad (3\text{-}9)$$

where:

CP = Cracking plus patching, $m^2/1000m^2$

R = Roughness, cm/km

RD = mean rut depth, cm

These equations permit the model to estimate structural deterioration with changing roughness. The next step requires the determination of the change in roughness as associated with maintenance effort,

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**Equations noted by ** are the result of empirical relations or regression analysis. The units often do not work out properly. In these cases the reader may imagine the components to be multiplied by some unit factor Q which will yield the specified units.

equation 3-10,

$$R = 79.0 + 2.96\ RD - \sqrt{CP}^{**} \qquad (3\text{-}10)$$

where:

RD and CP are repaired quantities.

To illustrate the simulation of maintenance operations as a function of deterioration and specified maintenance policy consider the following:

$$NA = \left[(CP)_x - (CP)_{x-1} \right] X\ WOS\ X\ LOS\ X\ 1000\ m/km \qquad (3\text{-}11)$$

where:

NA = area of new cracking on the pavement section, m^2

WOS = width of section, m

LOS = length of section, km

The maintenance policy for sealing and patching are specified as fractions of new cracking that will be sealed or patched.

$$SMS = FTS \times NA \qquad (3\text{-}12)$$

$$SMP = FTP \times NA \qquad (3\text{-}13)$$

where:

SMS = Area sealed, m^2

SMP = Area patched, m^2

Specified in maintenance policy $\begin{cases} FTS = \text{fraction of NA to be sealed} \\ FTP = \text{fraction of NA to be patched} \end{cases}$

Now the new area of cracking after maintenance, NA', is given by

$$NA' = NA - (SMS + SMP) \qquad (3\text{-}14)$$

3.2.4 Maintenance Quantities and Costs*

To transform the quantities of maintenance required (in this case

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*This portion of the program is taken from the previous work of Alexander (22). The explanation is altered only slightly from the original.

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 may be thought of as an automated estimating procedure. 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.

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

$$EHN_{ij} = \frac{CCM_{ij}}{PT_2} \times \frac{DOP}{100} \times SMP \qquad (3\text{-}15)$$

In equation 3-15, EHN_{ij} represents the hours of j type equipment needed to accomplish i type maintenance operations for the year. 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), DOP is the average depth of patch placed in centimeters, SMP represents the square meters of patching as determined by equation 3-13 and 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 3-15.

Estimating the quantity of materials required is a straight-forward 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:

$$MP_{ij} = EHN_{ij} \times C_{ij} \qquad (3\text{-}16)$$

Where MP_{ij} represents liters of gasoline required for the j type of equipment to accomplish the i operation: EHN_{ij} is determined in equation 3-15 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:

$$MBA_i = \frac{DCG \times DOP \times SMP}{100} \qquad (3\text{-}17)$$

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

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.

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

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.

3.2.5 Input-Output

The preceding detailed descriptions have sought to recount the rationale behind the formulation of the current model. It is perhaps unclear just what quantities the computer program requires as input. Furthermore the output quantities may be vague.

Table 3-1 lists both the type of factor and its measure needed as input for damage estimation. Additional input is required for the maintenance estimating routine. A thorough treatment of the input details is given in Appendix II, User's Manual.

Typical output includes:

(1) the number of equivalent coverages;
(2) the amount of cracking and patching before and after maintenance;
(3) average roughness for each period or year;
(4) the changes in roughness;
(5) the average vertical acceleration for the year and;
(6) the yearly and accumulated actual and discounted costs.

This output sequence is continued for any one project until either the number of periods of simulation or the allowable vertical acceleration is exceeded. A copy of the output for year 1 of one run is given in Figure 3-7. A more comprehensive description is not included here. However the reader is again referred to Appendix II for a full description of the program's requirements and capabilities.

3.2.6 Review of Details of Maintenance Model

In review, one should again examine the flow of the maintenance model. Figure 3-3 is schematically designed to explain the flow of operation which the computer model of maintenance follows.

The model provides the designer with the capability to test various combinations of construction quality and maintenance effort. Furthermore, it permits the designer to test a particular combination of construction and maintenance under changing climatic and traffic demand environments. For maintenance management, the model yields estimates of the performance consequences of various specified maintenance programs. Maintenance management may also test a given maintenance policy against varied traffic and climatic environments. In both cases, the model will predict damage and estimate the flows of cash, material, men, and machines under various input constraints as presented in Table 3-1.

One should remember that the maintenance model as presently constructed, will serve as an estimating tool. Consequently, as experience is gained with its use both the model's accuracy and usefulness will improve.

TABLE 3-1

Input Factors Influencing The Damage Estimation Of Airfield Pavements

FACTOR	MEASURE
1. Construction Quality	1. (a) Pavement Thickness
	(b) CBR Of Subgrade
2. Traffic	2. (a) ESWL
	(b) Tire Inflation Pressure
	(c) Number Of Coverages
3. Environment	3. (a) CBR - Design
	(b) CBR - Spring
4. Maintenance Effort	4. (a) Fraction of Cracks Filled
	(b) Fraction of Cracks Sealed
	(c) Fraction of Rut Depth Filled

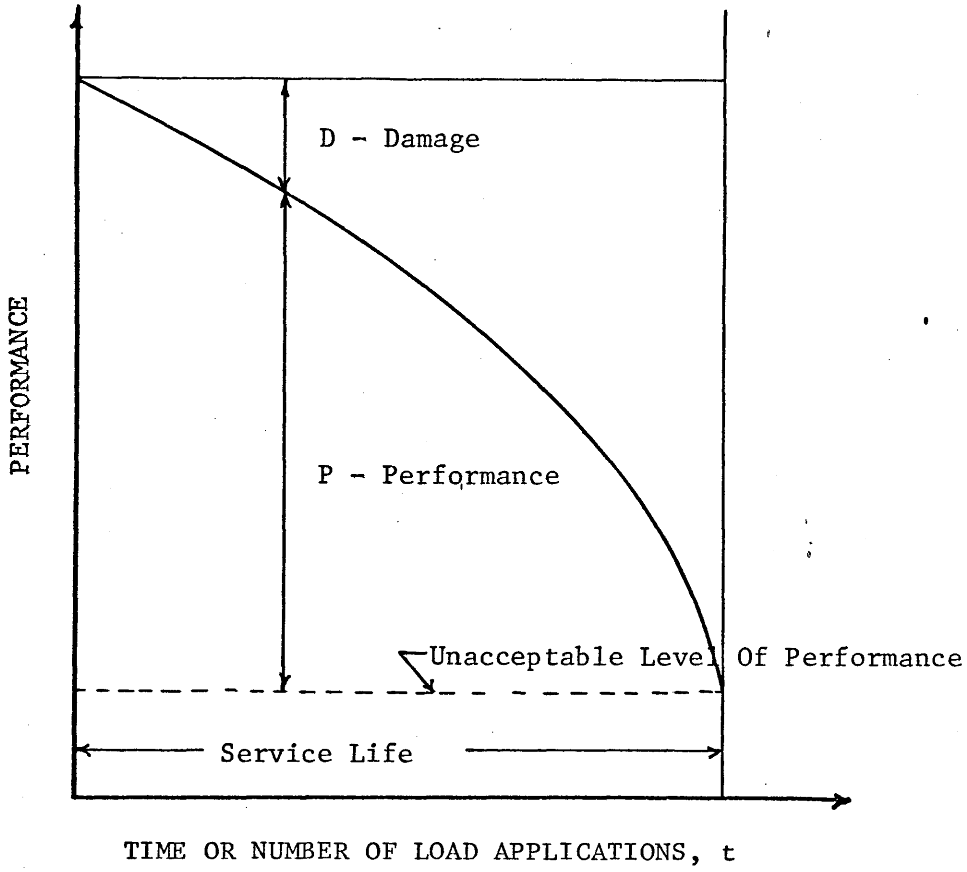

Figure 3-1: Concept Of Performance And Damage

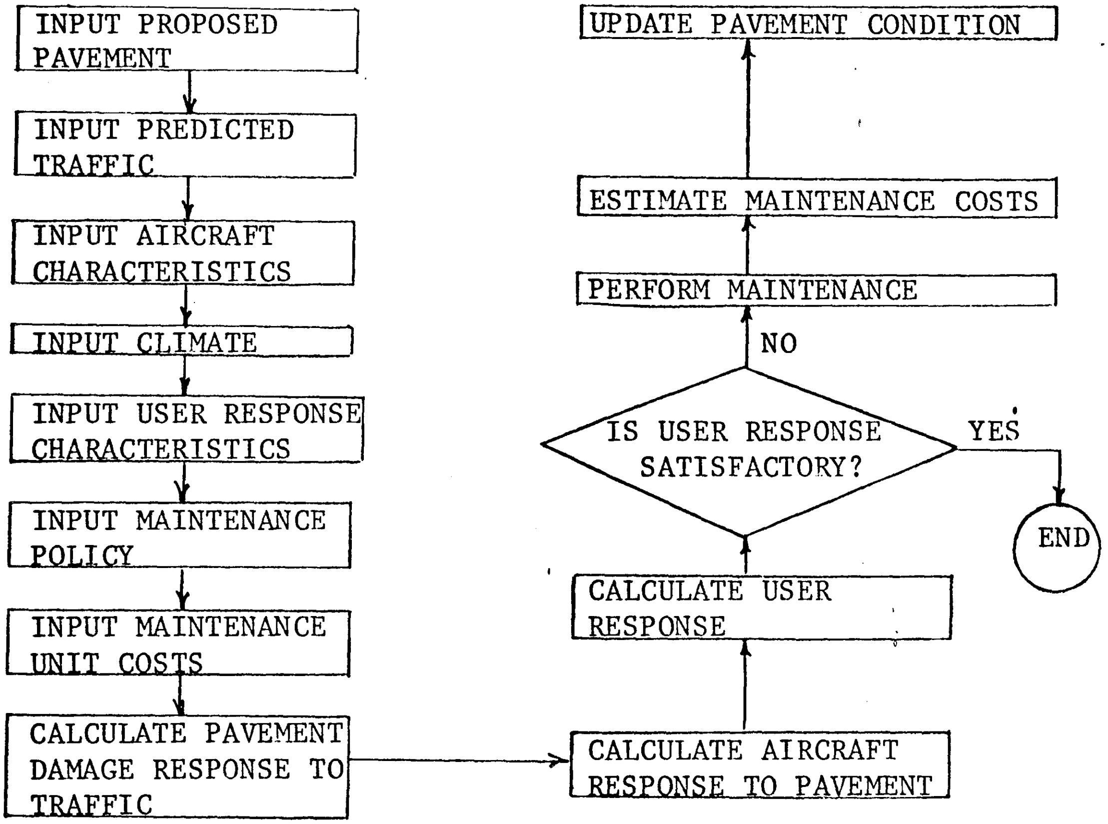

Figure 3-2: Flow Chart Of Ideal Concept Of Simulation Model

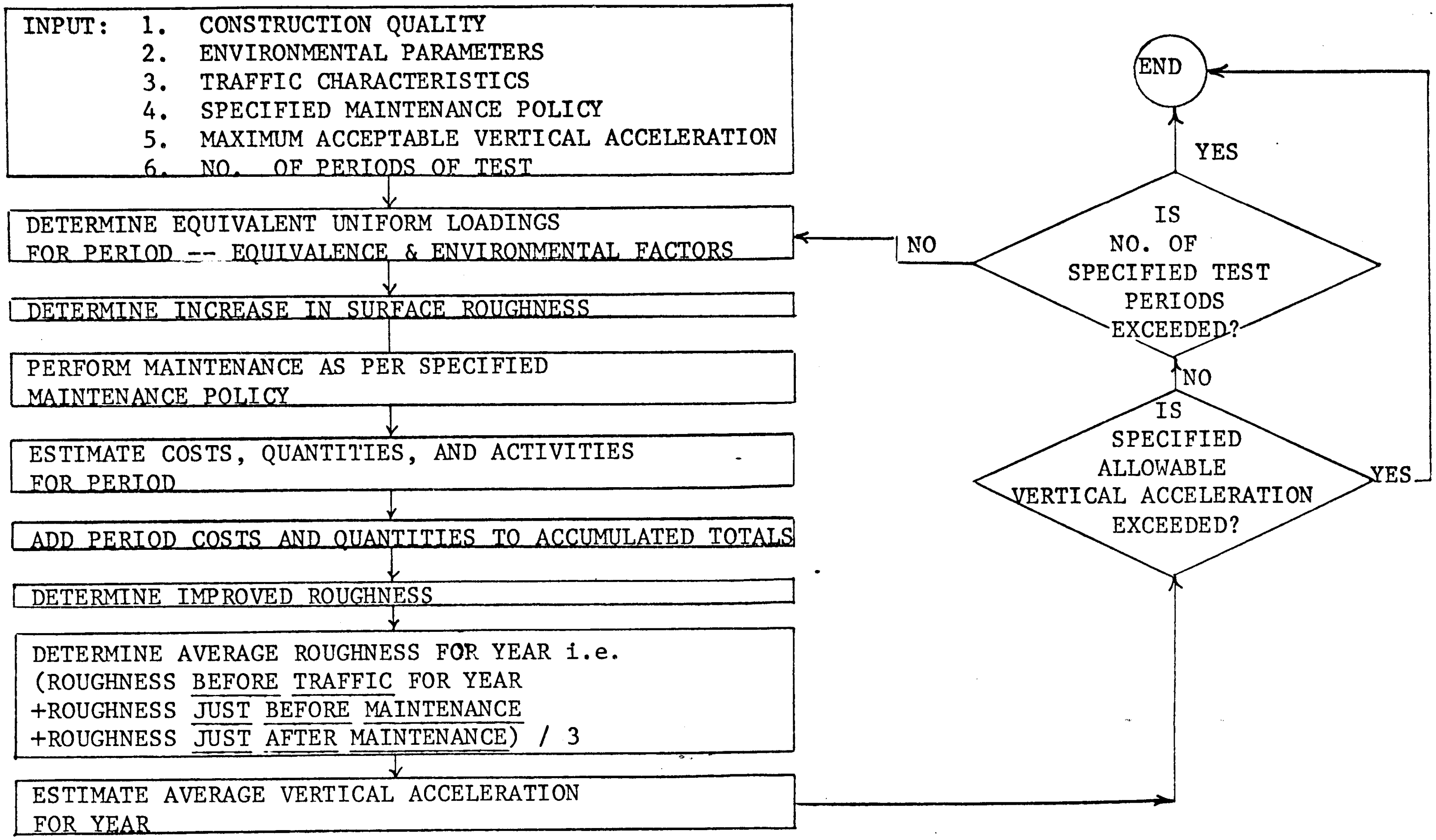

Figure 3-3: Detailed Schematic Of Maintenance Model

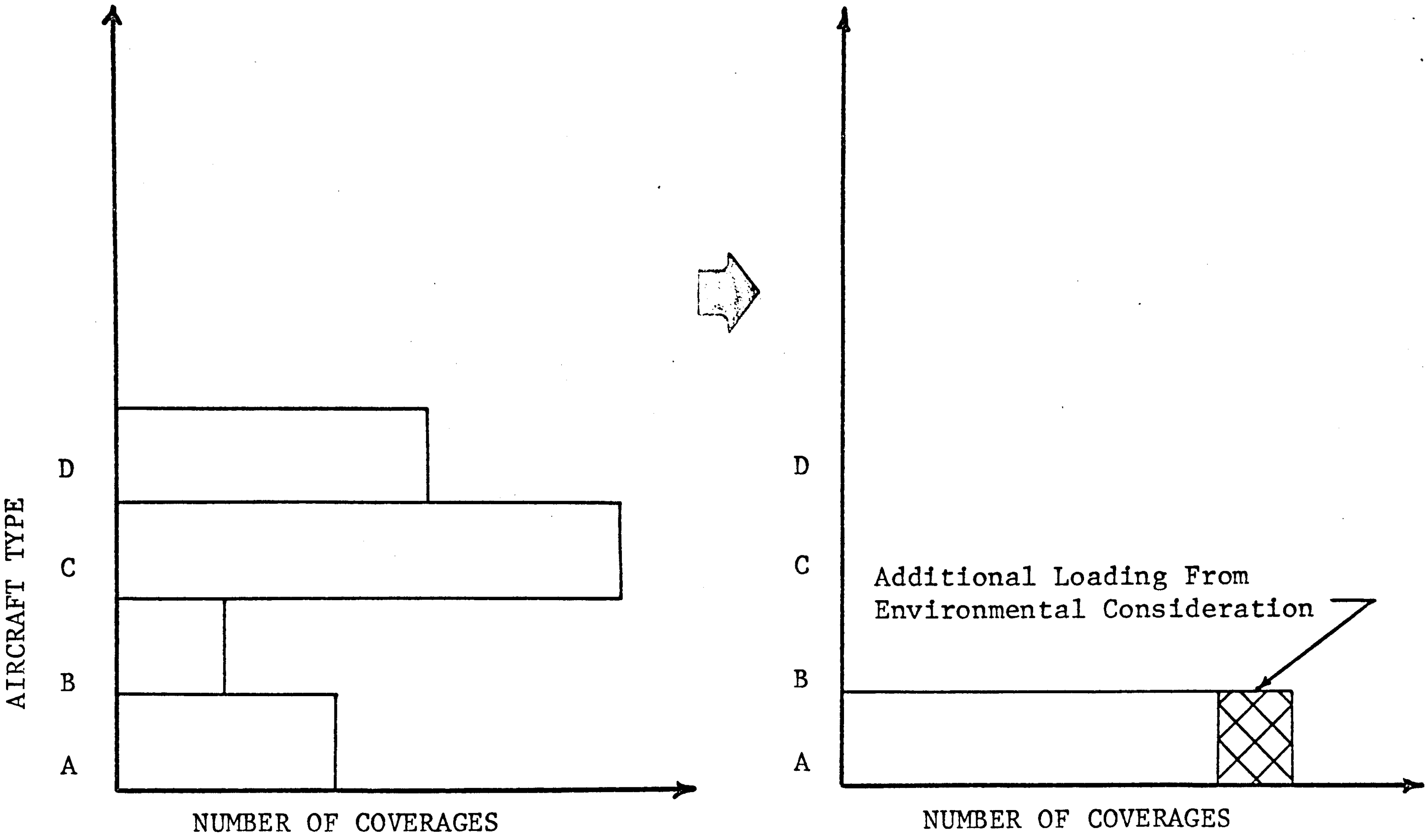

Figure 3-4: Schematic Of Equivalent Coverage Function

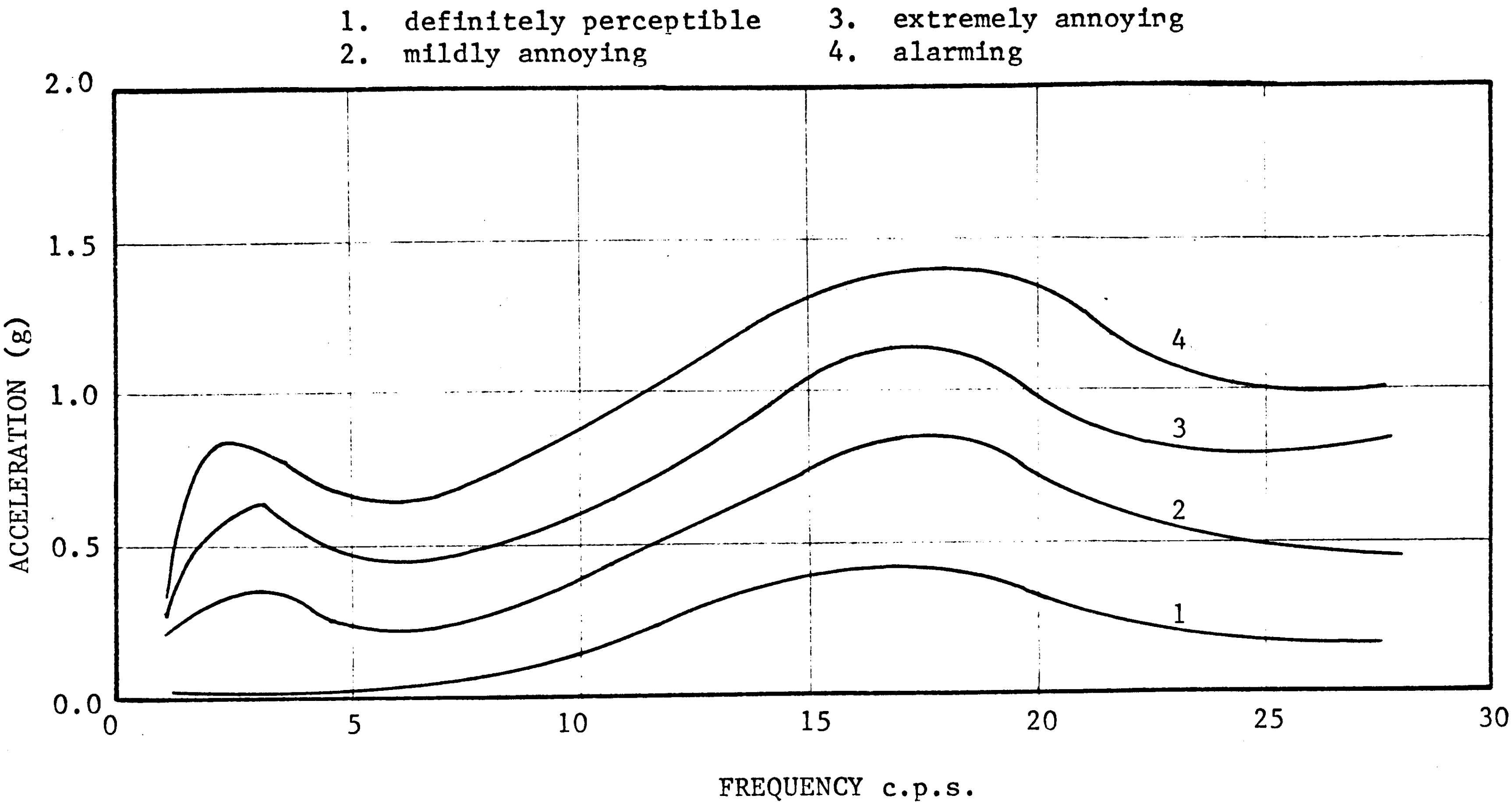

Figure 3-5: Subjective Response Data From Parks (14,37)

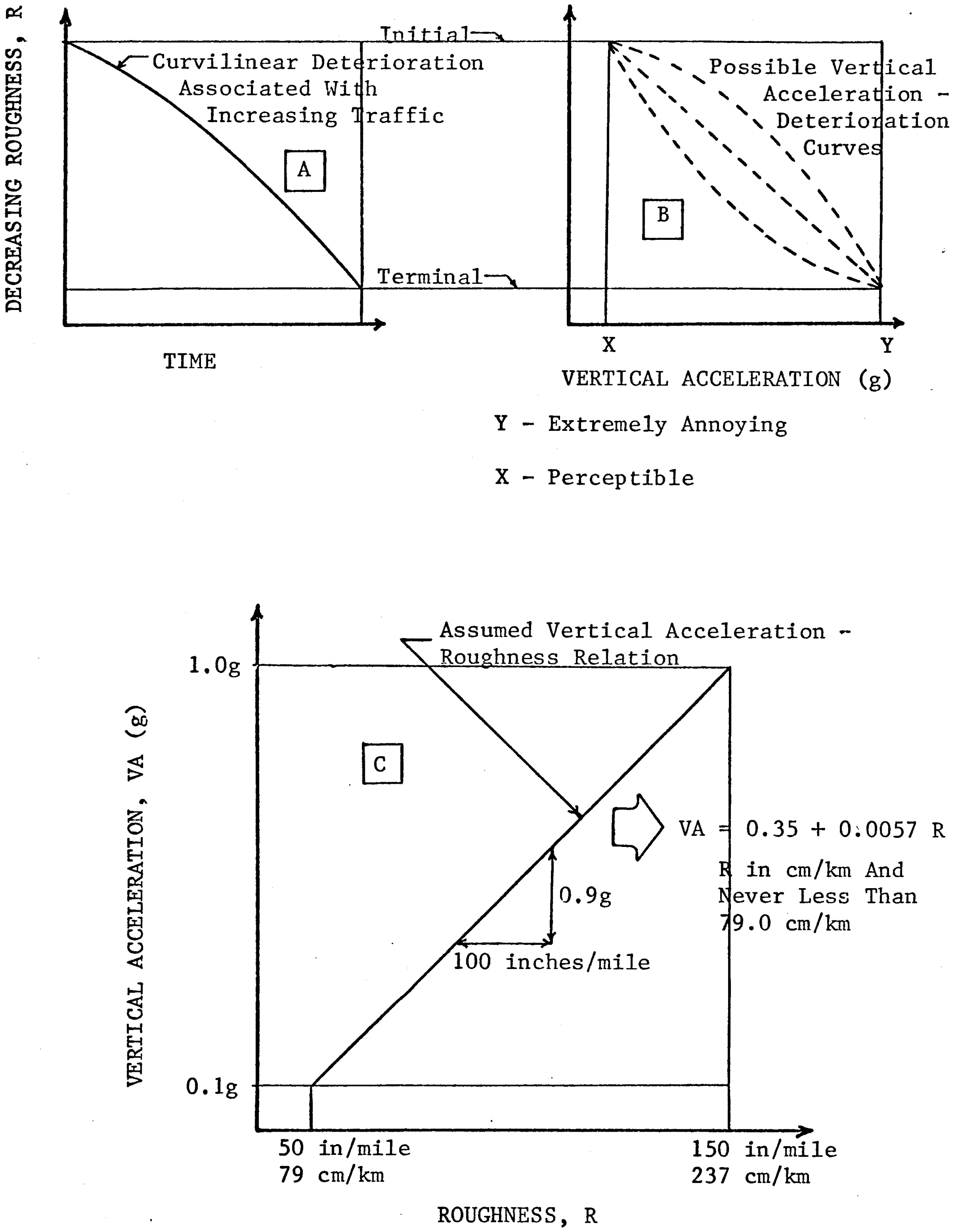

Figure 3-6: Schematic Relation Of Vertical Acceleration, Time, Roughness

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                                                  YEAR =       1

 NTYPE =       6

TYPE AIRCRAFT    NO. COVERAGES    EQUIV. COVER
     1               100.00           100.00
     2               100.00           167.02
     3               100.00           167.02
     4               100.00             1.80
     5               100.00             5.63
     6               100.00           783.79
 TOTAL EQUIVALENT COVERAGES FOR YEAR =    1225.27
 TOTAL UNIFORM COVERAGES, SAME OR REFEED,=     1270.19
 ACCUMULATED COVERAGES =            1270.19
 RGHNG =      14.38       RUFF =      93.38       PRUFF =      79.00
 C+P,BEFORE MAINTENANCE =      56.36       RD,BEFORE MAINTENANCE =       7.38
 CRACKING AND PATCHING, AFTER MAINTENANCE =      22.55       RUT DEPTH AFTER MAINTENANCE =       7.38
     DELCP       DELRD      SMP       SMS        CMPR       FIXRD      FTP       FTS
   2578.62       7.38    773.59    773.59       0.0        0.0       0.30      0.30

 YEARLY COSTS


                  DISCOUNTED COSTS          ACTUAL COSTS
 LABOR COSTS          9186.43            9829.48
 EQUIPMENT COSTS      1622.05            1735.59
 MATERIALS COST       2119.71            2268.09
 TOTAL COSTS         12928.19           13833.16

 ACCUMULATED COSTS


                  DISCOUNTED COSTS          ACTUAL COSTS
 LABOR COSTS          9186.43            9829.48
 EQUIPMENT COSTS      1622.05            1735.59
 MATERIALS COST       2119.71            2268.09
 TOTAL COSTS         12928.19           13833.16
 AVERAGE ROUGHNESS FOR YEAR        89.49

 AVERAGE VERTICAL ACCELERATION FOR YEAR         0.16
```

Figure 3-7: Typical Maintenance Program Print Out

CHAPTER IV

RESULTS AND DISCUSSION

This chapter addresses itself to the questions concerning the validity of model response and the use of the model. In order to consider these questions this chapter is divided into two sections, sensitivity analysis and tradeoff analysis, which discuss the problems of validity and of use respectively.

4.1 SENSITIVITY ANALYSIS

The purpose of this sensitivity analysis is threefold. It seeks to:

1. Examine the validity of the maintenance model response;
2. Isolate the input parameters and hence the computer program functions which have the most effect upon model response; and
3. Delineate areas in need of further research or calibration.

In the context used here, the first of these, validity, does not imply accuracy. Rather it is sought to examine the response trends of the airfield pavement maintenance computer program. In order for the program to be valid, the predictions which it makes should agree with those pavement response trends which have been observed both in the field and in the lab. After the program has been checked for validity it may be calibrated, i.e. it should be modified so that it predicts accurately the responses which occur in service. Calibration thus implies further work which will require substantial field data. In order to calibrate the model most efficiently it is desirable to isolate the input parameters and functions which effect the model's operation most significantly. If these are known the data acquisition and program modification which should be part of further research or calibration can be planned easily and effectively.

The strategy used in this sensitivity analysis involves the selection of a "standard" set of data which may be altered, one parameter at a time, and then compared with the results of other alterations. The standard set of data which was selected is given in Table 4-1, and is called the base run.

4.1.1 Variables Considered

It is the objective of this sensitivity analysis to examine only those airfield maintenance input variables which are of primary concern to the design and maintenance process. The parameters tested and presented herein are:

1. Thickness of pavement, T
2. Spring thaw subgrade support, SCBR
3. Design subgrade support, DCBR
4. Traffic
   a. coverages (repetitions), ANUMB
   b. loading (equivalent single wheel load, ESWL), P
   c. tire inflation pressure, PC
5. Maintenance unit costs, MUC - labor, equipment, and material
6. Maintenance policy, MAPOL
   a. fraction of rut depth filled, FRF
   b. fraction of cracks sealed, FTS
   c. fraction of cracks patched, FTP

Functionally, the maintenance model deals with these by predicting (a) maintenance cost and (b) runway pavement condition. Several output parameters are available for monitoring as listed in section 3.2.5. Those chosen were:

a. vertical acceleration (VA),
b. accumulated discounted total maintenance cost, and
c. the year in which VA equalled or exceeded 0.7 g.

The cumulative effect of damage or deterioration, cracking, patching, ruts, and roughness, is incorporated in the model response as VA and hence the selection of (a) for monitoring. The cost of maintenance, (b), was an obvious choice since its prediction is one of the major objectives of the thesis. Together with maintenance cost and facility condition it is necessary to know the expected service life, (c), of the facility. Therefore when VA $\geqq$ 0.7g the ability of the facility to meet the requirements of an adequate service level is significantly impaired and the facility is considered failed (see section 3.2.2). Each time a parameter is altered the service life of the facility may change. It would be quite difficult to compare the costs and performance as affected by parameter variation unless some constant length of time is chosen as a basis for comparison. Five years was selected as this time for two reasons: (a) because almost all of the projects survived that long and (b) because it is of special importance if reconstruction, upgrading, or staged construction are of interest (see references (69) and (70) for details).

The standard set of data in Table 4-1 gives the following results for comparison:

VA at five years = 0.46g
Accumulated discounted total cost
    of maintenance at five years = \$83,955
Year VA $\geqq$ 0.7g = 8.

4.1.2 Results of Analysis

Pavement thickness, T, was varied from -50% to +50% of the base run value, 71.12cm. The tabulated results of these are given in Table 4-2. At a thickness of 35.56 cm (-50%) the pavement rapidly deteriorates and fails within the first year. On the other hand a small increase in thickness of 10% lengthens the service life of the pavement approximately six years. A response trend of this sort should be expected from what is generally known about pavement design. This type of interaction (service life, maintenance cost, and pavement thickness) has been observed and reported by Witczak (71), the U.S. Corps of Engineers (56,57), and the U.S. Federal Aviation Administration* (72).

Spring thaw subgrade support, SCBR, exhibits only limited variation in facility service, cost, and life as shown in Table 4-3. A spring subgrade support value 80% less than the design or fall CBR value decreases facility life by only 25%. However it should be recalled that in this analysis merely 20% of the yearly traffic traverses the pavement during this critical time. Hence, this parameter may show marked changes in the response of the facility with substantial increases in traffic (73). Nevertheless, the parameter SCBR is not deemed overly significant unless the traffic distribution for the year is exceedingly difficult to predict.

Design subgrade support, DCBR, Table 4-4 is probably one of the most important parameters. The proper evaluation of this quantity is especially important in view of the design and deterioration assumptions made using the Corps of Engineer's method (equations 3-2 and 3-3). Since these equations use DCBR as an important parameter, the model should accurately reflect this importance. Furthermore, the deterioration of pavement is suspected of being related to the quality of the subgrade (74-76). Hence changes in DCBR should be accompanied by substantial changes in serviceability and costs. This is exactly what the model predicts. Changes in DCBR of +10% and -10% yield service lives of eleven and five years respectively.

Traffic variables, coverages, equivalent single wheel loads, and tire inflation pressure, all cause significant variations in response of the runway pavement. The results of sensitivity tests performed on these three parameters are given in Tables 4-5, 4-6, and 4-7. Equivalent single wheel load exhibits the most substantial effect while tire inflation pressure shows much less variation. The number of coverages causes variation somewhere in between.

Coverages per year were varied by ±10%, ±30%, and ±50%. Typical

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*This assumes that the material of construction is the same or of equal quality.

service lives were 12 years for -50%, 7 years for +10%, and 6 years for +30%. The costs and VA varied as shown in Table 4-5. Variations of ±10% and ±30% were conducted for load and tire pressure. An increase in ESWL of +30% results in the failure of pavement at 3 years instead of the base run figure of 8 years. Tire inflation pressure shows only moderate changes from the base run results. This is to be expected since only small changes in the intensity of load usually accompany increases in tire pressure (77).

The trends shown in the traffic analysis seem to correspond quite well with airfield and highway pavement experience gained at the WASHO (27), and AASHO (63) road tests and the Stockton (78) and other U.S. Corps of Engineers full scale tests (12).

Maintenance unit costs, MUC, Table 4-8, were varied ±10% and ±25%. The resulting costs of maintenance varied in the same manner by percentage. Individual unit costs were not varied. However it is recognized that individual prices influence the percentage costs of equipment, material and labor. To this end the maintenance costs have been broken down percentage-wise by (a) individual components and (b) groups, Table 4-9. It is clear that the division which will prove most beneficial is labor costs. It should be noted that this breakdown is peculiar to U.S. prices. The relative size of the components will change from country to country, depending upon the degree of labor or capital intensity (see Hirschman (80)). The division of costs between labor, equipment, and material appears to be valid. This may be supported from trends observed for the U.S. in both the Dodge Estimating Guide (81) and the National Construction Estimator (82).

Maintenance policy, MAPOL, Table 4-10, is probably the most interesting evaluation. Tests were run on fraction of cracks patched, FTP, fraction of cracks sealed, FTS, and fraction of rut depth filled, FRF. The most peculiar results occur when one examines the relation between increased values of FTS and FTP (FRF = 0.0) and the vertical acceleration at five years. Instead of more maintenance leading to increased serviceability the serviceability decreases i.e. vertical acceleration increases. The simplest way to explain this phenomenologically is to recall the technique by which cracks are patched (includes crack filling) and sealed. Generally it is difficult to repair a crack in such a manner that it will be flush with the pavement surface (83). The patching or sealing material protrudes above the surface and may increase the amount of surface roughness slightly. Evidently this effect of crack maintenance, patching, is reflected in equations 3-7, 3-8, 3-9, and 3-10. The regression analysis used to determine the form of several of these included both cracking and patching. Hence this reaction of the model seems justifiable; but since the regression analysis relied upon highway measurements (AASHO (63)) rather than airfield data, the implications of these results require verification with field data. Another question arises when one notes that the costs and vertical acceleration are lowest when FTP and FTS equal zero. If one assumes that the subgrade support is not affected by the seepage of water from surface cracks this is probably a valid phenomena. However most studies in the area (74-77, 27, 63, 78, 79, 83) have found that subgrade support should vary with the amount of seepage allowed. Hence crack maintenance is required. The seepage of water ultimately affects the spring subgrade support and hence this is the parameter which must be accurately estimated under various crack maintenance programs. Therefore the values of VA at five years for zero and non zero crack maintenance may not be readily compared unless different SCBR values of subgrade support are used. This further implies that in order to avoid changes in the pavement structural support, it is necessary that cracks be filled and patched. Therefore, the extent of patching and filling is directly related to the rate of deterioration.

The repair of rutting shows the most marked influence on the parameters of cost and vertical acceleration (via roughness equations 3-7 and 3-10). The assumption which are associated with this substantial cost accumulated in filling ruts are perhaps in error.* Another potential cause for both cost and VA results lies in the use of the AASHO data (63) to determine the constants and form of equation 3-7 and 3-10

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*For a thorough presentation of these assumptions see Appendix V, Assumptions Concerning Maintenance.

and especially equation 3-9. However the accuracy of these predictions may only be determined by comparison with actual data. Variations in fraction of rut depth filled, FRF, from 0.1 to 1.3 have been studied. The life of the facility under these FRF's varied from 8 years to 19 years respectively. Accordingly, the parameter FRF is the most influential variable under maintenance policy (both in terms of model response and associated assumptions). And it may have far reaching effects upon the remainder of the model simulation.

4.1.3 Discussion of Sensitivity Results

The foregoing results of sensitivity analysis show that:

a. Those references which have been cited tend to support the predictions which the model makes.

b. From an a priori view the model functions well and predicts responses which are reasonable in terms of increments or decrements e.g. increased thickness implies larger maintenance costs and decreased service life.

The results of the sensitivity analysis demonstrates that the model developed is most sensitive to the following parameters:

1. pavement thickness, T
2. design subgrade support, DCBR
3. traffic weight, P
4. fraction of ruts filled, FRF.

(It should be noted that these results are to be expected in keeping with the inherent assumptions in the design equations which have been used.) In order to numerically examine the effects which these have upon the model operation their values were changed by either 10% or 1/10 fraction and the percent change in output (see section 4.1.1) was monitored. The results are tabulated in Tables 4-11 and 4-12. The results show that the four parameters mentioned above are extremely influential upon the response of the airfield maintenance computer program. Therefore these parameters should receive primary attention in further work because it is apparent that the accuracy of these determine largely the accuracy of the output (response) of the model as a whole. Consequently, the functions or equations and assumptions which relate these input parameters to the output should be investigated. A review of Chapter III and Appendix V shows that the effect these parameters exhibit is highly dependent upon equations 3-2, 3-9, and A-V-1*.

In the decision making process of the airfield desiger, operator, or maintenance manager it is most useful to know what design or maintenance parameters effect the performance of the pavement most. The preceding sensitivity analysis has identified these. Hence the next consideration concerns tradeoff analysis.

4.2 TRADEOFF ANALYSIS

The decision maker for an airfield pavement design or maintenance policy is confronted with a large number of parameters from which to construct the facility or to derive a maintenance policy. However as was shown in the sensitivity analysis he may be able to confine the majority of his considerations to four parameters**: (a) pavement thickness, (b) design subgrade support, (c) weight of aircraft, and (d) fraction of ruts to be filled.

In all cases the decision maker, designer, operator, maintenance manager, or planner, should be concerned with at least two issues: (a) the total cost and (b) the performance of the facility. He should

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*Equation 1 in Appendix V

**When examining these parameters it should be remembered that most of the relations in this model are correlative. They are not analytical derivations. Hence the responses predicted at this stage of development are most probably inaccurate in terms of magnitude.

recall that the components of total cost, maintenance cost, user cost, and construction cost, are not independent variables. Furthermore it should be remembered that to attain higher performance operations more effort and generally more cost is inherent. It may also be useful to recall that the right amount or proper balance of maintenance for one may not be the same for another. Hence, the selection of a design or a maintenance policy should be made within the context of the particular facility's total environment (i.e. political, economic, climatic, etc.,). Therefore as this presentation continues no effort will be made to pick any one most suitable strategy.

The tradeoff analysis which follows examines maintenance cost and facility service with time. Maintenance costs are monitored as accumulated discounted total maintenance costs. Therefore the time stream flow of costs may be inspected for each potential project. Facility service is characterized by the predicted vertical acceleration, VA, for each project. The choice of VA has already been discussed in section 3.2.2. It should be noted that the program as it now exists uses this parameter from a safety standpoint; i.e., the ability of the pilot to perform ground movements safely while undergoing a VA of 0.7g is significantly impaired. Referring to Figure 3-5 one can observe that the monitoring of this parameter allows the prediction of the aircraft's crew or passengers psycho-physical response to the airfield pavement's condition. At a vibration rate of 5 cps a VA of about 0.25g is only mildly annoying whereas a VA of 0.7g may be alarming. If one assumes that the VA-roughness relation (equation 3-7) is accurate and that the prevailing frequency of vibration is 5 cps the prediction of serviceability may be usefully extrapolated to allow user costs to be examined. This implies that the force impinging on the landing or taxiing aircraft together with its frequency (5 cps) could be predicted and used to examine the damage and cost of damage to the airframe and to cargo as caused by the runway.

On the other hand since this reflects the service perceived by the user the interaction of maintenance and serviceability may be considered by varying the maintenance policy and monitoring VA. Furthermore the relationship between maintenance and reliability may also be investigated in a simplistic manner. This implies that a maintenance policy which increases the time during which $VA < 0.7g$ produces a facility which has a higher probability of meeting service demands than a project with a less effective maintenance program (all other things being equal, section 2.1.2).

What follows is the result of testing various values of pavement thickness, design subgrade support, aircraft weight, and maintenance policy (FRF). For each of these parameters, two curves have been plotted: time versus maintenance costs and time versus VA. Accompanying each of these is a discussion of the tradeoff analysis which a decision maker might consider.

4.2.1 Results of Tradeoff Analysis*

The proper selection of a pavement thickness, T, is one of the prime decisions to be made in the design of airfield pavements. Of course it is evident that this requires some analysis of initial cost versus future maintenance cost. However the service which the facility provides is also quite important. A look at Figure 4-1 shows clearly that the maintenance cost and service life under a constant maintenance policy changes with the pavement thickness. Figure 4-2 shows the serviceability, in terms of VA, that the facility may provide with time as related to the pavement's thickness. At this stage only two alternatives are available. The decision maker may choose a predicted serviceability which suits the needs of his facility and automatically be forced to select a certain pavement thickness; or he may choose a pavement and be confined to a specific predicted serviceability.

To increase the number of degrees of freedom which are available, a change in maintenance policy should be considered. It was proposed in section 2.2.3 that increased maintenance effort for a constructed facility could change its service characteristics. Again these changes

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*All parameters are at their base run value unless specified.

are also noticed in terms of maintenance costs. Figures 4-3 and 4-4 exhibit the costs, service, and time relationships which might be considered for a pavement having a thickness of 71.12 cm (base value) with changing maintenance effort (FRF). However these maintenance policies assume that maintenance is an on-going process and is distributed throughout the course of each year. Maintenance may be accomplished by concentrating the necessary work into short periods occurring at reasonably long intervals (i.e. maintenance may be carried out at intervals of two, three, four, or five years or more). The cost and service results for such a process are shown in Figures 4-5 and 4-6. As an example of the results of such a process, consider the two year interval (Figures 4-5 and 4-6) and the maintenance policy having FRF = 0.3 (Figures 4-3 and 4-4). The two year interval process has a service life of 11 years with a cost of $5.6 million while the continuous policy costs $2.2 million more for only one additional year of service. If the additional year of service is not an essential requirement of the pavement it may be cheaper to institute maintenance at two year intervals rather than to distribute it over every year.*

It is clear then that tradeoffs exist among pavement thickness and maintenance operations. Two other effective parameters are the subgrade support of the runway and the weight of the aircraft which will use the pavement. The design subgrade support, DCBR, can influence both the selection of the pavement thickness (equation 3-2) and the deterioration of the pavement's service. If only DCBR is varied, cost and service effects appear as in Figures 4-7 and 4-8. The physical variation of this parameter may be accomplished in at least four ways: (a) replacing the existing subgrade soil with a higher quality material (higher potential California Bearing Ratio), (b) mixing cement or other chemicals with the subgrade to raise its quality, (c) using a larger

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*Maintenance which occurs during short time periods and at long intervals might be accomplished by contracting or renting equipment as opposed to owning the necessary equipment and maintaining the men and organization required for a continuous effort. By specifying the factor prices (costs of men, machines, and material) each of these alternatives can be investigated.

compactive effort to increase the DCBR, or (d) selecting a sight which has a high quality subgrade already present. Each of these four techniques may effect costs substantially. Therefore DCBR may influence a wide range of cost properties as well as the service of the pavement. Thus the evaluation of this parameter deserves much of the attention of the decision maker.

The last parameter to be considered here is aircraft equivalent single wheel weight. Variation of this parameter by as little as ±10% can cause significant changes in maintenance cost and service, Figures 4-9 and 4-10. The evaluation of the effects of this parameter allows the designer to determine the adequateness of his design and the maintenance manager the adequateness of a given maintenance program. This allows adjustments to be made either in design or in maintenance. An alternative might involve the discouragement of the landing of overly heavy aircraft. Thus landing fees may be altered to induce aircraft operators to reduce their "all up" weight or to find other suitable airfields for their operations.

All of the variables which the airfield maintenance computer program considers have not been analyzed. Nevertheless, those which were found by sensitivity analysis to produce substantial changes in model response (output) in comparison to small input changes have been investigated. A discussion of the results of this tradeoff analysis follows.

4.2.2 Discussion of Tradeoff Analysis

The results of tradeoff analysis have shown graphically the effects which pavement thickness, maintenance policy (FRF), aircraft weight, and pavement subgrade support may have upon both maintenance costs and serviceability. It is however necessary for the decision maker to select a combination of these parameters which best fits the needs of the particular airfield pavement in question. The combination which might be selected for Kennedy International Airport would most likely be different than the selection for Raleigh-Durham Airport (North Carolina).

Not only do these airports operate under different economic environments but they also must provide different levels of service. It should be noted that a primary concern at Kennedy International is to guard against failure and the impairment of pavement service. Therefore it may be more reasonable to provide a high degree of construction quality such that only small amounts of maintenance, which will not interfere with the pavement's ability to serve traffic, is required (8). On the other hand Raleigh-Durham Airport is not subjected to extreme demands upon its service (84). Hence the adoption of a thinner pavement thickness along with a more liberal intense maintenance policy may be suitable. This implies that interruption of service for maintenance purposes will probably not result in substantial inconvenience or cost to the users of the airfield pavement.

Other problems which may be faced concern the subgrade support which the proposed or existing location should or does provide. Four methods of changing the DCBR of a location have been mentioned in section 4.2.1. And it has been recognized that a certain amount of cost is involved with each of these. Tradeoffs between initial effort and future maintenance effort exist here. For example, a site which has a low subgrade support may be chosen with the understanding that substantial future maintenance effort will be required. Nonetheless the predicted performance of the facility under this strategy should be comparable to one having low maintenance and high initial effort. Furthermore from an economic viewpoint the total cost of the high maintenance project should be lower or more suitable (time stream flow of capital) than for this large initial effort strategy. For an already existing pavement, it may be difficult to improve the subgrade support. However it is apparent from Figures 4-7 and 4-8 and Table 4-11 that DCBR can have a major effect upon the deterioration of service and thereby the results of any proposed maintenance policy.

In review it is apparent that the three above discussed parameters and aircraft weight have substantial effects upon the airfield pavement's maintenance cost and performance. These four parameters should be the ones with which the decision maker is most interested because only small changes in their values can have large effects upon the response of the airfield pavement. It has furthermore been noted that the results of tradeoff analysis involving pavement design, deterioration, and maintenance at one airport should not necessarily correspond with those at another facility in a different environment. Hence it is the decision maker's job to select those quantities which will provide the desired level of service under an appropriate maintenance policy at a reasonable level of reliability for an acceptable cost. While the airfield maintenance program cannot solve this problem for the decision maker, it can be used as an efficient tool to aid in his evaluation.

TABLE 4-1

Base Run Data

1. Maintenance policy, (MAPOL)

fraction of ruts filled, FRF = 0.0
fraction of cracks patched FTP = 0.3
fraction of cracks sealed, FTS = 0.3
mean rut depth allowable, MRD = 2.0 cm

2. Unit costs for maintenance*, (MUC)

bituminous distributor, UEDS = $ 4.00/hour
dump truck, UEDT = 3.00
tractor loader, UELD = 3.00
motor grader, UEMG = 3.75
roller, UERL = 4.10
water truck 6 cu. m., UETR = 0.00
water truck 7 cu. m., UEWT = 0.00
common labor, ULC = 5.25
equipment operator, ULEO = 7.17
foreman, ULF = 8.20
truck driver, ULTD = 6.68
liquid asphalt, UMB = 0.04/liter
bituminous aggregate patch mix, UMBA = 6.60/M. Ton
cover aggregate for sealing, UMCA = 3.45
delivered diesel fuel, UMD = 0.04/ liter
gravel at source, UMG = 3.58/M. Ton
gasoline, UMP = 0.07/liter
water at source, UMW = 0.00/cu. m.

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*Unit costs taken from, National Construction Estimator, 1970-71 (82) and Dodge Estimating Guide (81).

3. Number of different type aircraft, NTYPE = 6
4. Design CBR, DCBR = 10.0%
5. Thickness of pavement, T = 71.12 cm.
6. Width of pavement, WOS = 45.75 m
7. Length of runway, LOS = 3.05 km
8. Spring CBR, SPRNG = 7.00%
9. Fraction of traffic during spring thaw period, SPTHW = 0.20
10. Fraction of traffic increase per year (coverages), TRINC = 0.10
11. Discount rate, DISCR = 0.07
12. Limiting acceptable vertical acceleration, VA = 0.7g
13. Traffic data:

TYPE	ESWL, P (kg)	Tire inflation pressure, PC, (kg/cm^3)	Coverages/year
1	28636.63	10.57	100
2	30909.09	11.63	100
3	30909.09	11.63	100
4	15909.09	9.16	100
5	18181.82	10.15	100
6	41818.18	12.68	100

TABLE 4-2*

Sensitivity Analysis: Thickness

Thickness		VA		Cost		Year
(cm)	% change	(g's)	% change	$	normalized	VA = 0.7g
35.56	-50	***	***	593,820	7.07	1
49.78	-30	***	***	158,253	1.88	1
64.01	-10	***	***	147,950	1.76	4
71.12	0	0.46	0	83,955	1.00	8
78.23	+10	0.24	-48	36,364	0.43	14
92.46	+30	0.13	-72	7,199	0.09	+20
106.68	+50	0.11	-76	2,273	0.03	+20

*For Tables 4-2 through 4-12 the following is important:

1. % change - change from base run values (for VA and costs at five years)
2. VA - Vertical Acceleration
3. costs - accumulated discounted total maintenance costs at five years
4. normalized - ratio of project costs to base run costs at five years
5. *** - project failed before five years - values reported are for last year of analysis

TABLE 4-3*

Sensitivity Analysis: Spring Thaw Subgrade Support, SCBR

SCBR		VA		Cost		Year
%	% change from DCBR	(g's)	% change	$	normalized	VA = 0.7g
10	0	0.44	-4	81,405	0.97	8
9	-10	0.45	-2	82,074	0.98	8
8	-20	0.45	-2	82,900	0.99	8
7	-30	0.46	0	83,955	1.00	8
5	-50	0.47	2	87,367	1.04	8
4	-60	0.49	7	90,513	1.08	7
2	-80	0.60	30	112,434	1.34	6

*See TABLE 4-2 notes.

TABLE 4-4*

Sensitivity Analysis: Traffic Repetitions

Coverages For First Year		VA		Cost		Year
Number	% change	(g's)	% change	$	normalized	VA = 0.7g
50	-50	0.28	-39	45,909	0.55	12
70	-30	0.35	-24	61,680	0.73	10
90	-10	0.42	-9	76,695	0.91	8
100	0	0.46	0	83,955	1.00	8
110	+10	0.49	7	91,066	1.08	7
130	+30	0.56	22	104,878	1.25	6
150	+50	0.63	37	118,198	1.41	6

*See TABLE 4-2 notes.

TABLE 4-5*

Sensitivity Analysis: Equivalent Single Wheel Loads, ESWL, (P)

ESWL	VA		Cost		Year
% change	(g's)	% change	$	normalized	VA = 0.7g
-30	0.16	-65	16,384	0.20	+20
-10	0.32	-30	53,533	0.64	11
0	0.46	0	83,955	1.00	8
+10	0.65	41	122,440	1.46	6
+30	***	***	131,976	1.57	3

*See TABLE 4-2 notes.

TABLE 4-6*

Sensitivity Analysis: Tire Inflation Pressure, PC

PC	VA		Cost		Year
% change	(g's)	% change	$	normalized	VA = 0.7g
-30	0.35	-24	60,231	0.72	10
-10	0.43	- 7	77,331	0.92	8
0	0.46	0	83,955	1.00	8
+10	0.48	4	89.616	1.07	8
+30	0.53	15	98,736	1.18	7

*See TABLE 4-2 notes.

TABLE 4-7*

Sensitivity Analysis: Design Subgrade Support, DCBR

DCBR		VA		Costs		Year
% (CBR)	% change	(g's)	% change	$	normalized	VA = 0.7g
7	-30	***	***	133,982	1.60	2
8	-20	***	***	171.347	2.04	4
9	-10	0.72	57	134,701	1.60	5
10	0	0.46	0	83,955	1.00	8
11	+10	0.31	-33	52,158	0.62	11
13	+30	0.18	-61	20,420	0.24	19
15	+50	0.13	-72	8,521	0.10	+20

*See TABLE 4-2 notes.

TABLE 4-8*

Sensitivity Analysis: Maintenance Unit Costs, MUC

MUC	VA		Costs		Year
% change	(g's)	% change	$	normalized	VA = 0.7g
-25	0.46	0	62,894	0.75	8
-10	0.46	0	75,480	0.90	8
0	0.46	0	83,955	1.00	8
+10	0.46	0	92,264	1.10	8
+25	0.46	0	104,837	1.25	8

*See TABLE 4-2 notes.

TABLE 4-9

Maintenance Cost Distribution

Resource		Percentage	
Labor	(Total)		71.56
	Common labor	43.74	
	Truck driver	26.96	
	Equipment operator	0.86	
Equipment	(Total)		12.93
	Dump truck	11.83	
	Other	1.10	
Material	(Total)		15.51
	Liquid Asphalt	0.82	
	Patching mixture	12.69	
	Gasoline	2.00	
	Total		100%

TABLE 4-10*

FTS	FTP	FRF	VA		Cost		Year
			(g's)	% change	$	normalized	VA = 0.7g
0.3	0.0	0.0	0.44	-4	5,110	.06	8
0.3	0.1	0.0	0.45	-2	25,862	.31	8
0.3	0.3	0.0	0.46	0	83,955	1.00	8
0.3	0.4	0.0	0.47	2	124,797	1.44	8
0.3	0.6	0.0	0.50	9	243,555	2.90	7
0.3	0.9	0.0	0.55	20	430,446	5.13	7
0.0	0.3	0.0	0.44	-4	54,408	0.65	8
0.1	0.3	0.0	0.45	-2	62,427	0.74	8
0.4	0.3	0.0	0.47	2	98,388	1.17	8
0.6	0.3	0.0	0.50	9	138,164	1.65	7
0.9	0.3	0.0	0.55	20	178,327	2.12	7
0.0	0.0	0.0	0.43	-7	0	0	8
0.3	0.3	0.1	0.43	-7	502,480	5.99	8

TABLE 4-10* (continued)

FTS	FTP	FRF	VA		Cost		Year
			(g's)	% change	$	normalized	VA = 0.7g
0.3	0.3	0.3	0.39	-15	1,277,741	15.22	10
0.3	0.3	0.6	0.33	-15	2,298,390	27.37	12
0.3	0.3	0.8	0.29	-37	2,893,067	34.46	14
0.3	0.3	1.0	0.26	-43	3,425,949	40.81	16
0.3	0.3	1.3	0.22	-52	4,121,270	49.09	19

*See TABLE 4-2 notes.

FTS - fraction of cracks sealed

FTP - fraction of cracks patched

FRF - fraction of ruts filled

TABLE 4-11*

Results Of Sensitivity Analysis For 10% Change ** In Input Parameter

	Cost		Vertical Acceleration		Service Life	
Rank	Parameter	% change	Parameter	% change	Parameter	% change
1	T	57	T	48	T	75
2	P	46	P	41	DCBR	38
3	DCBR	38	DCBR	33	P	25
4	MUC	10	ANUMB	6.5	ANUMB	12.5
5	ANUMB	8.5	PC	4.3	SCBR	0
6	PC	6.7	SCBR	1.1	PC	0
7	SCBR	0.7	MUC	0	MUC	0

*See TABLE 4-2 notes.

**From Base Run Values

TABLE 4-12*

Results Of Sensitivity Analysis For Maintenance Parameters, 1/10 Fractional Change**

Rank	Parameter	% Change in Cost	% Change in VA	% Change in Service Life
1	FRF	499	6.5	0
2	FTP	49	2.2	0
3	FTS	17	2.2	0

*See TABLE 4-2 notes.

**From Base Run Values

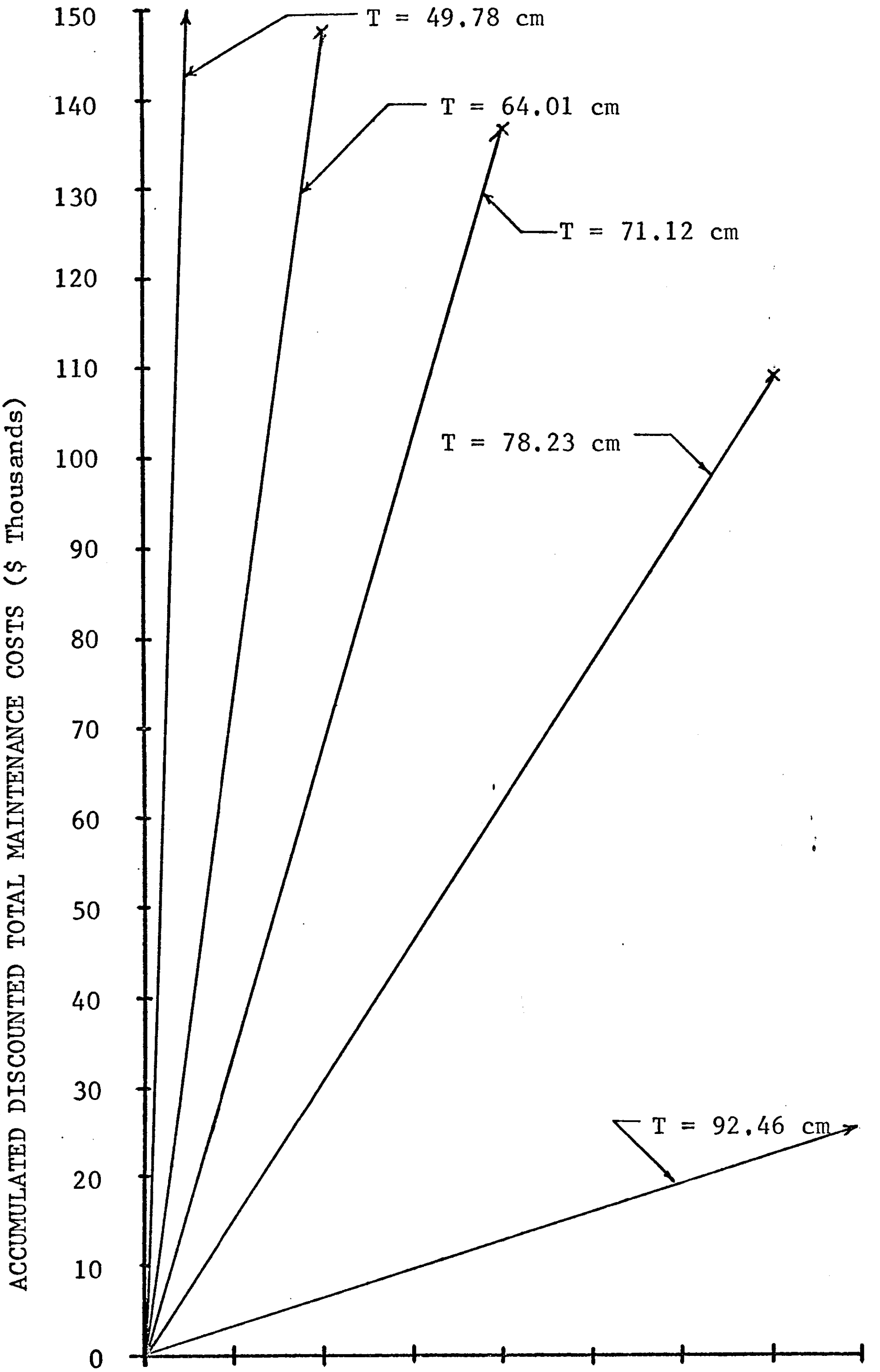

Figure 4-1: Maintenance Costs For Varying Pavement Thickness

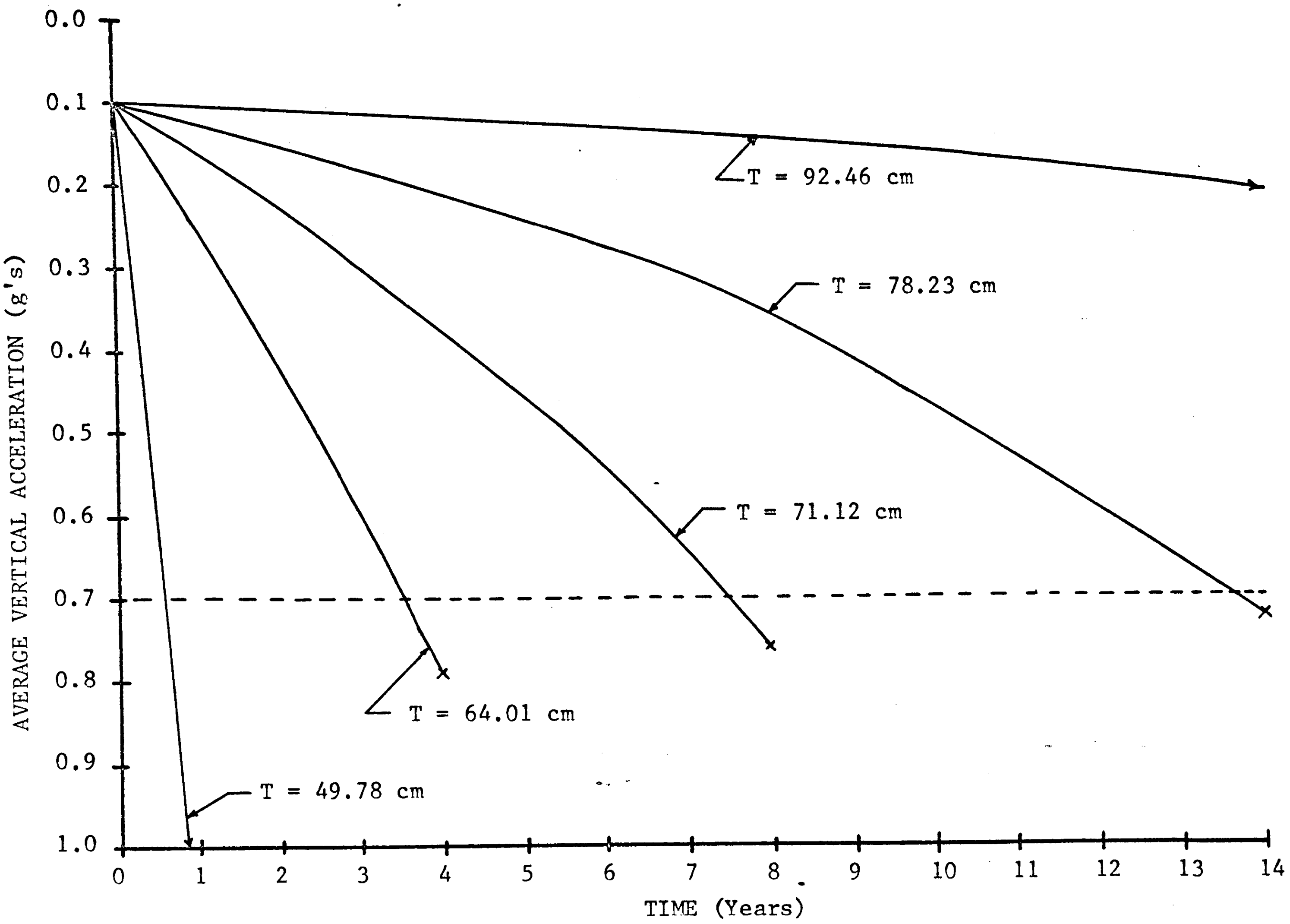

Figure 4-2: Vertical Acceleration Vs. Time For Varying Pavement Thickness

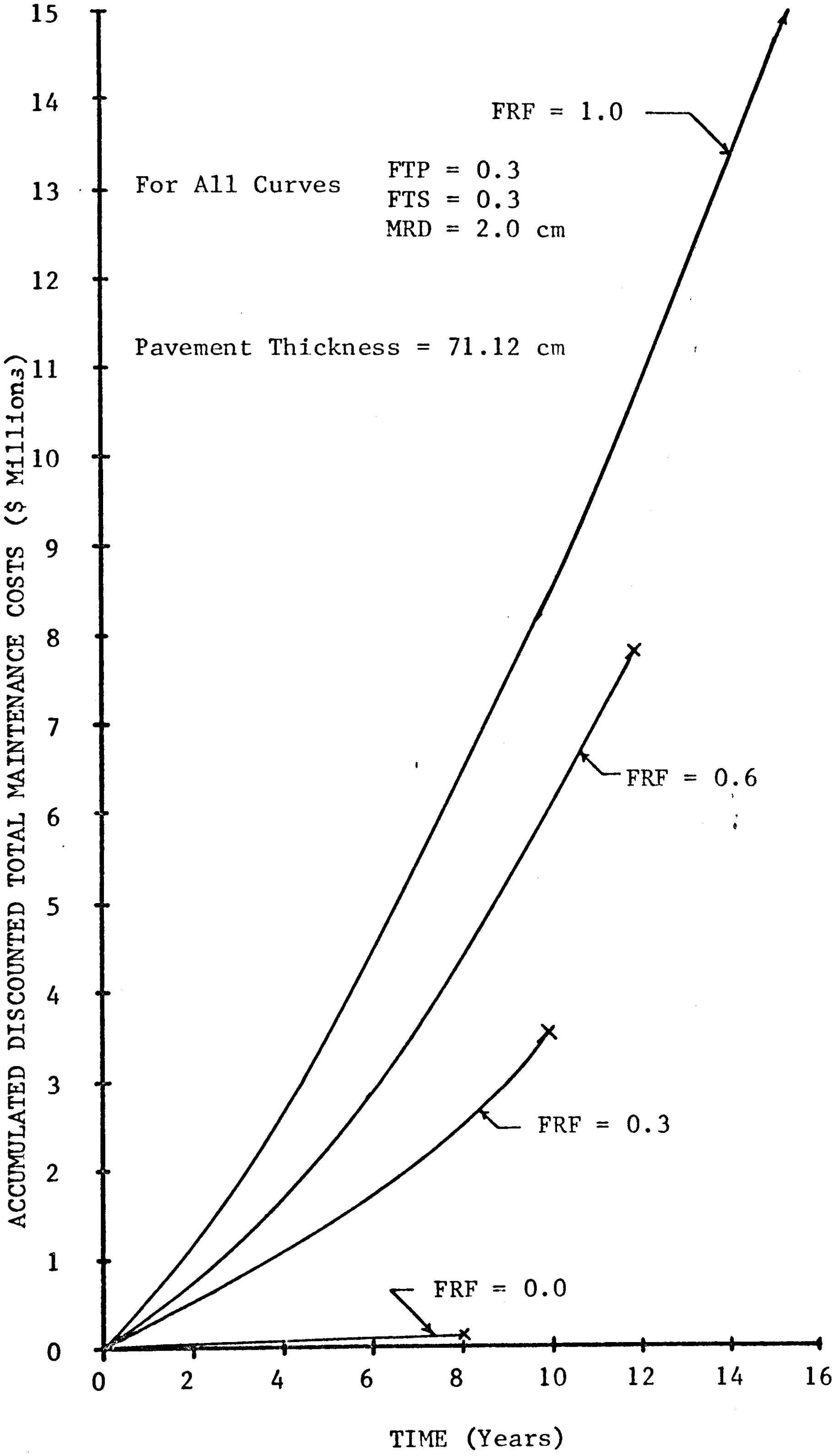

Figure 4-3: Maintenance Costs For Changing Maintenance Policy

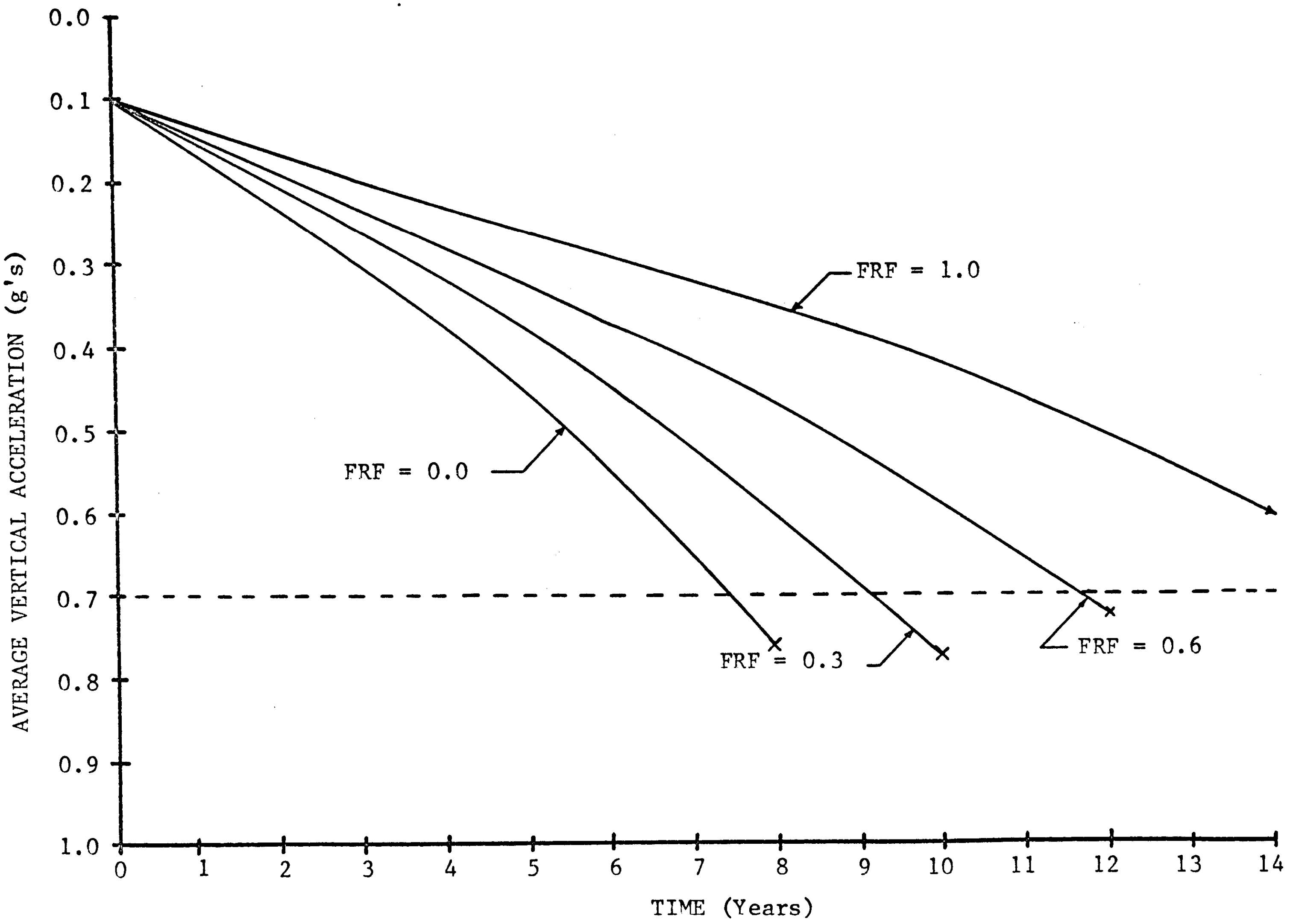

Figure 4-4: Vertical Acceleration Vs. Time For Changing Maintenance

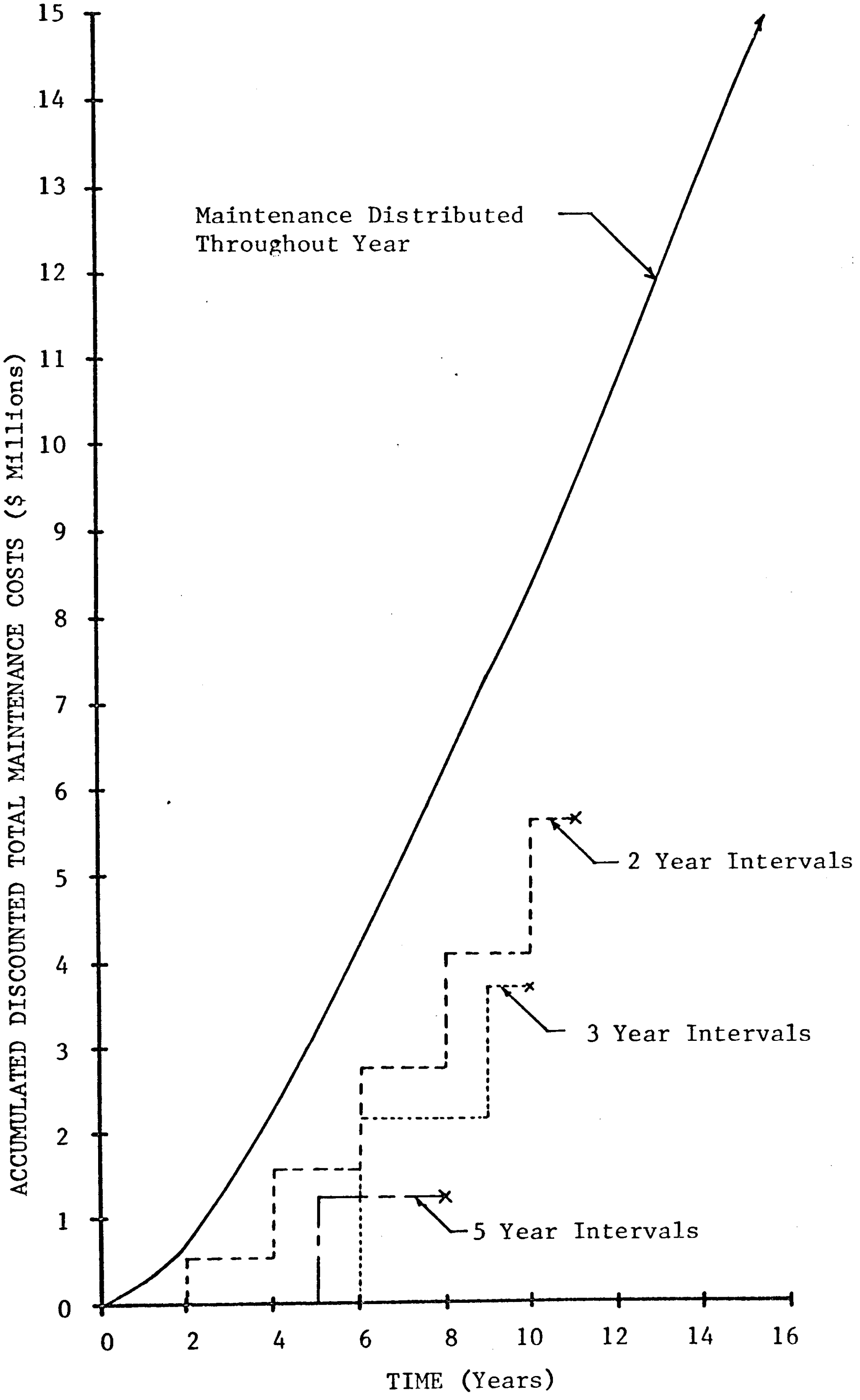

Figure 4-5: Maintenance Cost For Various Intervals Of Maintenance Application

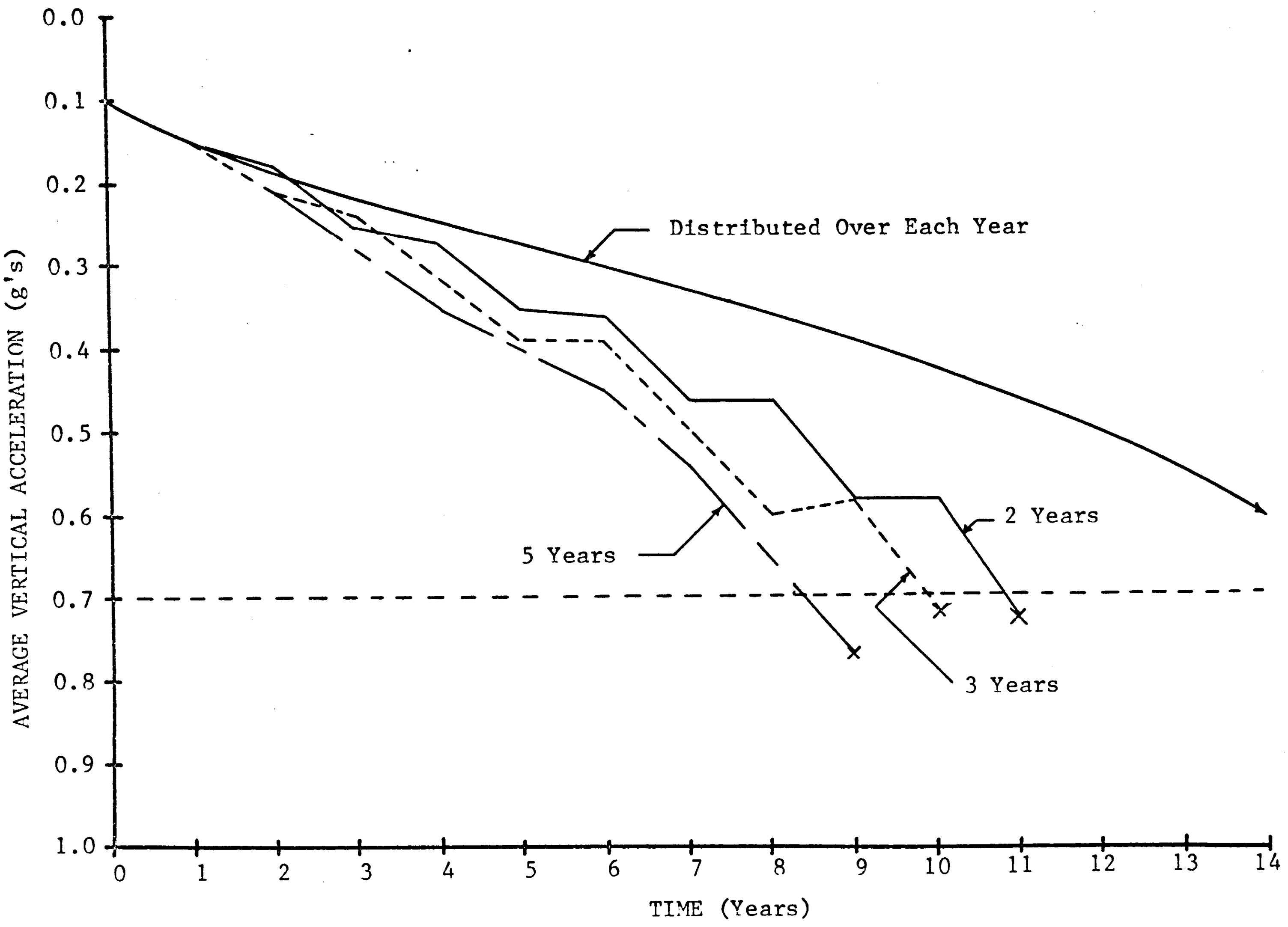

Figure 4-6: Vertical Acceleration Vs. Time For Several Intervals Of Maintenance Application

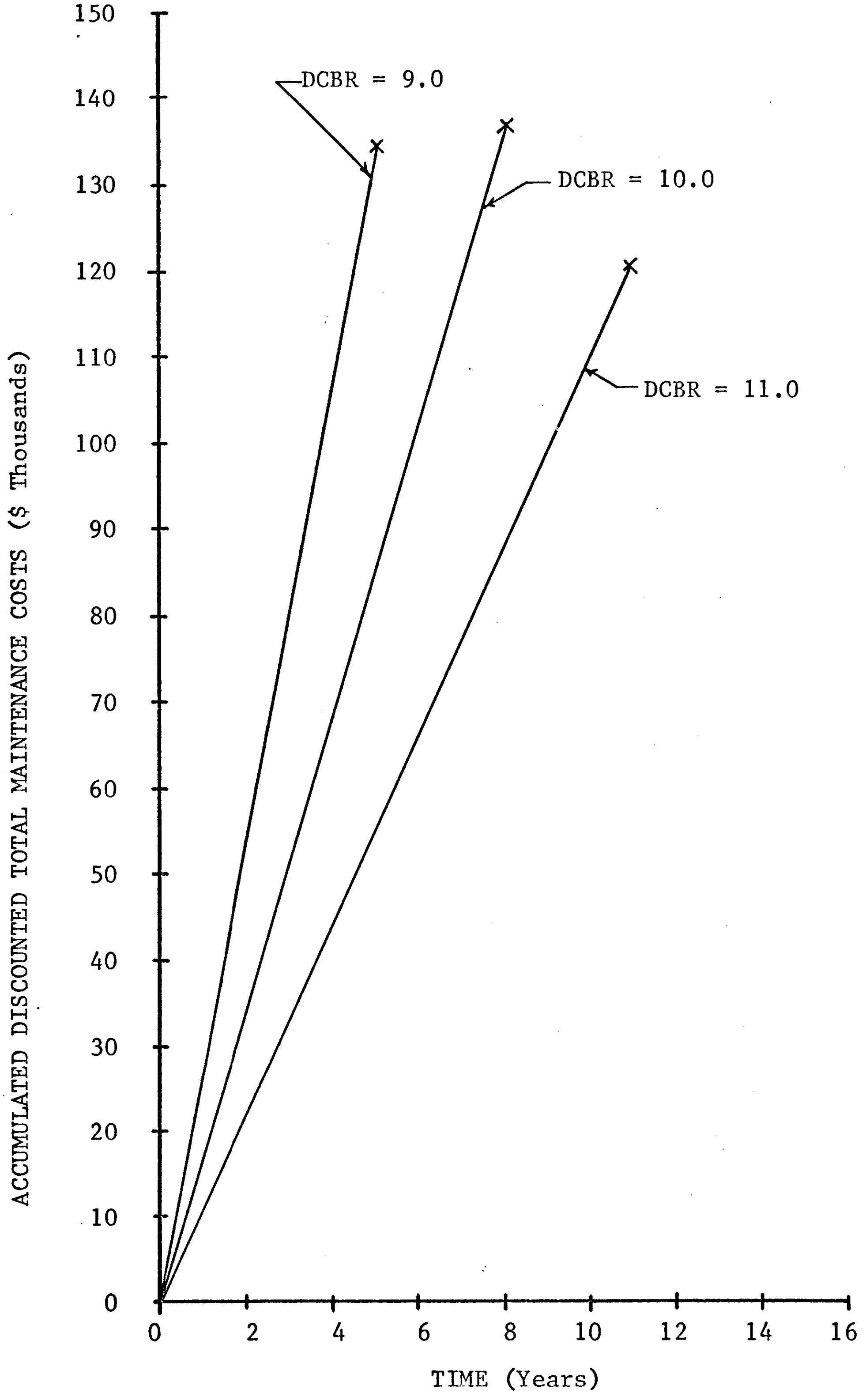

Figure 4-7: Maintenance Cost For Three Subgrade Support Values

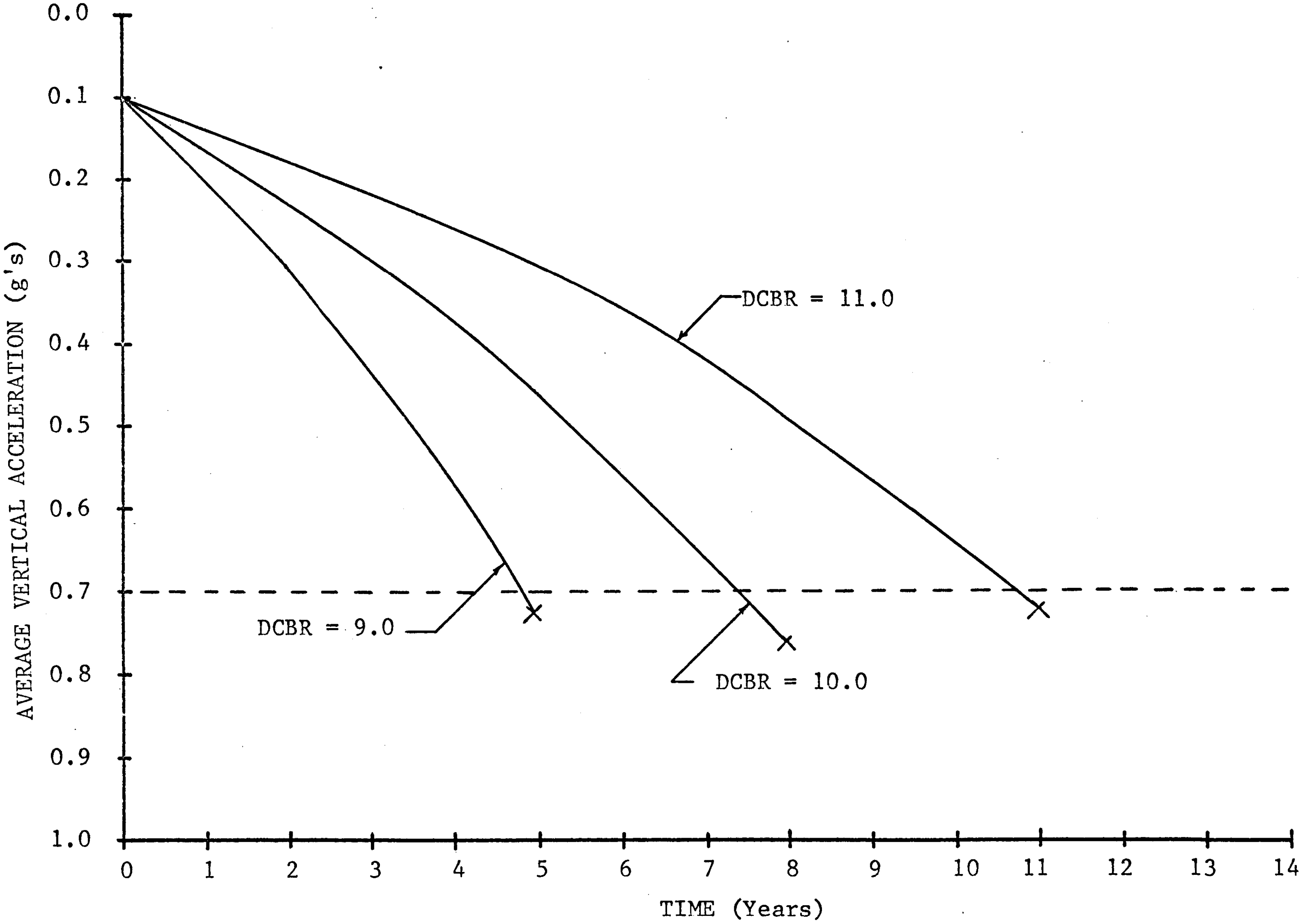

Figure 4-8: Vertical Acceleration Vs. Time For Three Values Of DCBR

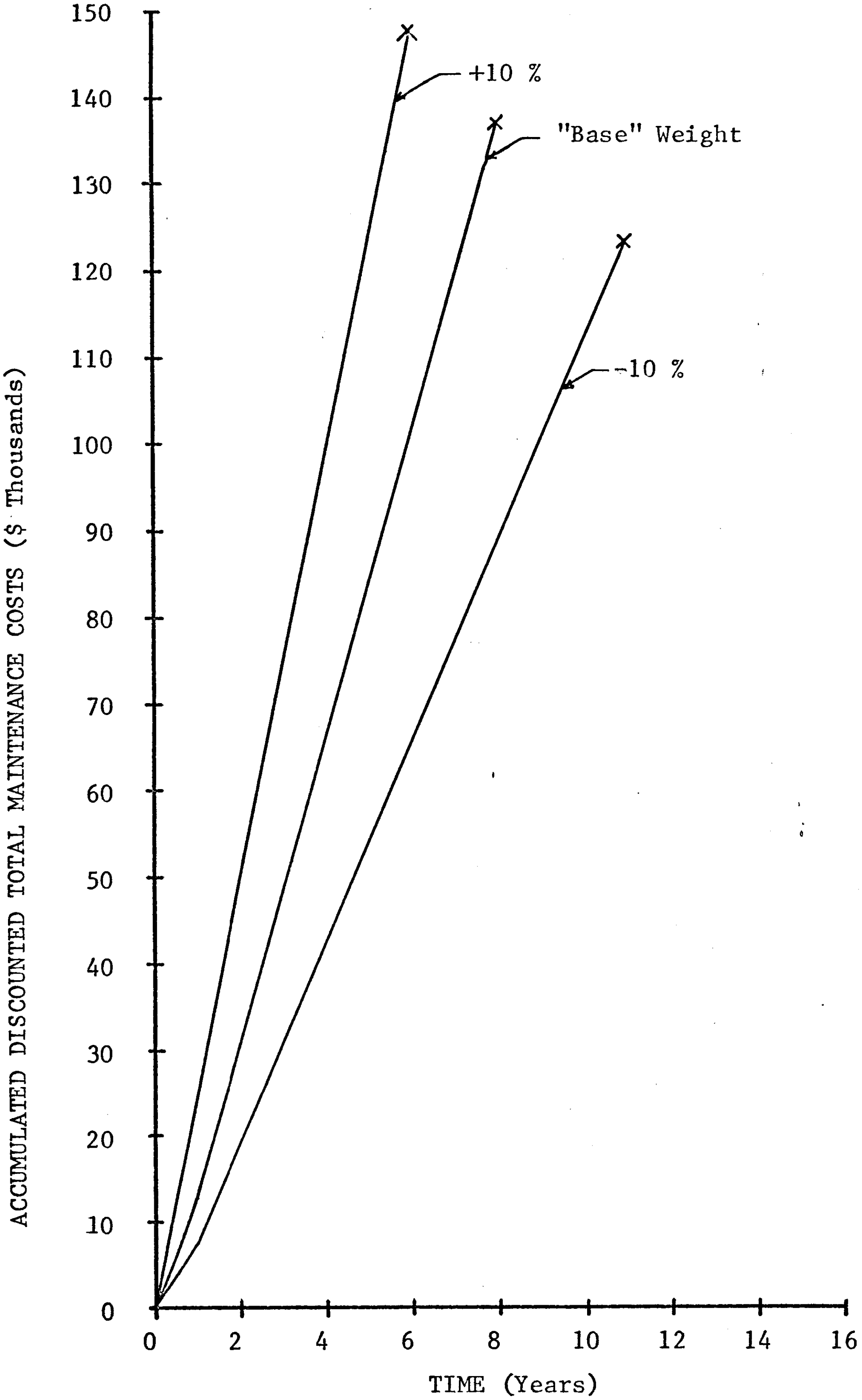

Figure 4-9: Maintenance Cost For Different Aircraft Loads

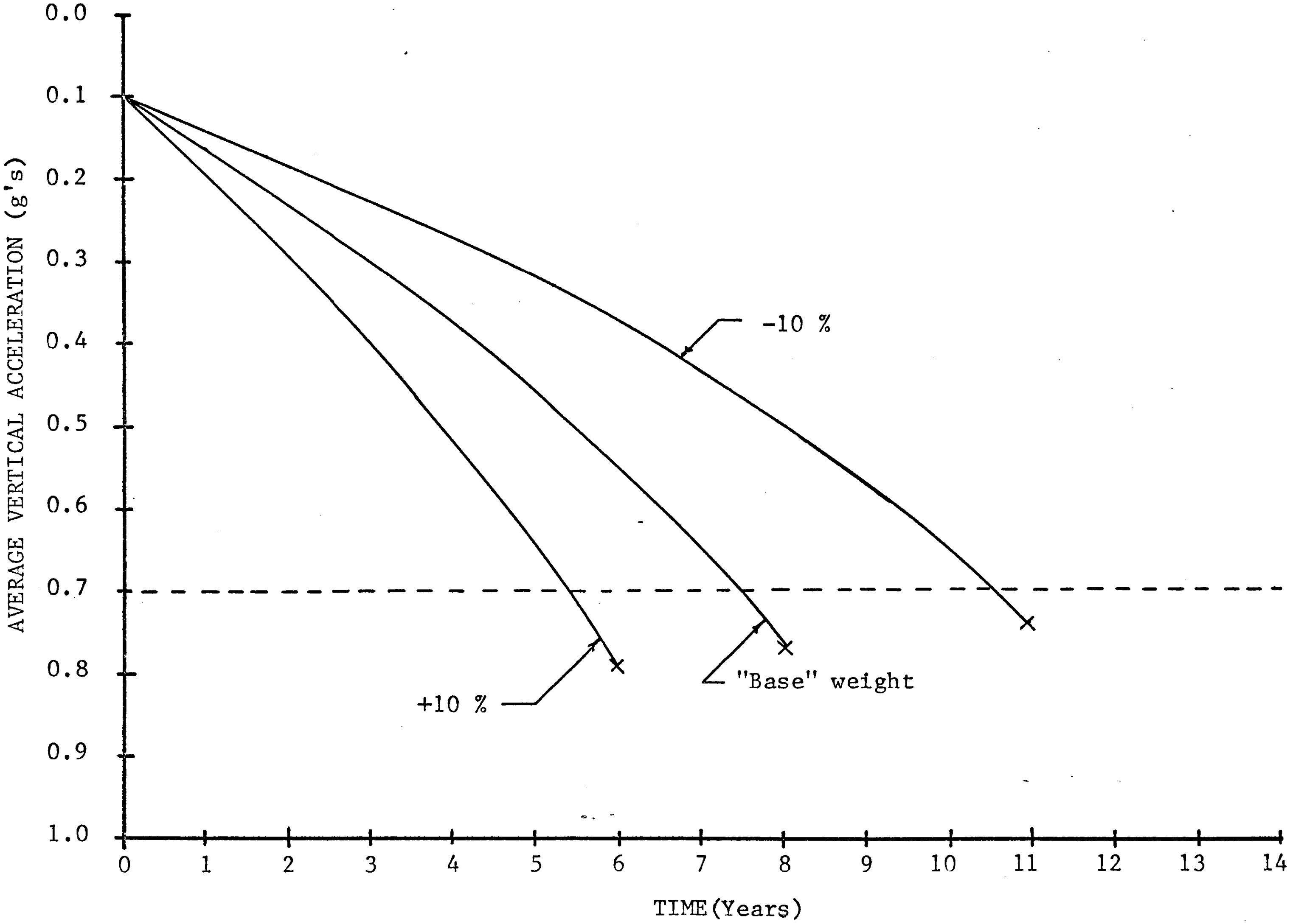

Figure 4-10: Vertical Acceleration Vs. Time For Three Aircraft Loads

CHAPTER V

SUMMARY, EVALUATION, AND RECOMMENDATIONS

5.1 SUMMARY

The two questions which were posed at the beginning of this thesis may now be dealt with in an objective manner. Recall that these questions were:

1. What is the best balance between initial system cost and future maintenance cost; and
2. How much maintenance should be done on existing facilities?

The maintenance model computer program provides the primary vehicle through which these questions may be evaluated for a particular facility in its own peculiar technical, economic, social, political, and climatic environment. The model itself predicts the condition of the pavement and the cost of specified maintenance operations throughout the facility's service life. Typical output of the model contains:

1. Accumulated and yearly equivalent traffic
2. Cracking and patching before and after maintenance
3. Mean rut depth before and after maintenance
4. Average roughness for each period or year
5. Average vertical acceleration for each period
6. Yearly and accumulated maintenance costs (both actual and discounted) broken down into equipment costs, labor costs, materials cost, and total cost.

The formulation of the airfield pavement maintenance computer program is based upon empirical relations (section 3.2). However the structure of the program relies upon the simulation (as realistically as possible) of the physical cycle of deterioration and repair. Hence the more common approach of relating pavement deterioration and maintenance costs to combinations of significant variables through simple regression analysis has been rejected (22). The cycle of deterioration and repair has been divided into its several physical activities. These are then simulated individually and combined by the computer program to predict the total system response (damage and performance).

The two major concerns of any constructed facility, costs and performance, have been discussed in detail. It is recognized that the two are not independent. There are several combinations of total cost which may produce facilities of similar performance. Furthermore it was noted that facility performance is composed of serviceability, maintainability, and reliability. These three measures may be varied together with costs to attain a desired performance.

The maintenance program allows the evaluation and prediction of costs and performance of a specified airfield pavement. Thus the program of itself cannot make the actual design, construction, and maintenance decisions but it can present the consequences of various strategies or decisions in terms of damage, serviceability (VA), and maintenance costs.

5.2 EVALUATION

The structure of the airfield pavement maintenance model seems to be conceptually sound. The model predicts reasonably valid pavement response to variation in design characteristics, traffic loads, climatic environment, and maintenance policy. Furthermore the model structure, which bases the maintenance cost estimates on the overall simulation of pavement behavior, appears to be practical for estimating future maintenance costs. During the numerous runs for sensitivity and tradeoff analysis no major inconsistencies in the model's operation have been observed. However one particular area concerned with the cost of rut repair does warrant further review and probably calibration since these costs seem substantial.

At present the model is capable of aiding the planner, designer, operator, or maintenance manager in addressing the two aforementioned questions of maintenance. However since the model has not been calibrated some futher work may be needed to make the model operational. Nevertheless even in its present form the model may be used to evaluate and compare cost and performance trends of various construction and/or maintenance strategies. Therefore if the user understands the accuracy limitation of the model, it may be used as a detector of most suitable strategies.

The further work that may be needed in the area of calibration can be accomplished at two levels. These are discussed in the next section.

5.3 RECOMMENDATIONS FOR FURTHER WORK

Two levels of calibration may be investigated. The first of these involves the collection of large amounts of traffic, deterioration, performance, and maintenance cost data. This data could in turn be used to calibrate the model; or to make it more accurate. The relations dealing with the most sensitive input parameters: (a) pavement thickness, (b) subgrade support, (c) traffic weight, and (d) maintenance policy (FRF) should be considered first. Work at this level should not require more than an additional year of research.

The second level of calibration might extend over a period of several years. It would involve the adaptation of the model to a specific locality or project. Thus the response of the model and the facility or facilities could be examined together. Hence adjustments in the model would accompany changes in the pavement condition. Conceptually, this type of trial application should result in general improvement of the model which will increase its accuracy for use in other areas.*

A much more ambitious recommendation concerns the combination of calibration and extension of the current model. At first this would involve the refinement of many of the damage prediction functions such as equations 3-8, 3-9, 3-10. Further concern would involve a more thorough investigation of the performance prediction relating roughness and vertical acceleration. To a degree these might constitute calibration. Extending the model refers to the addition of construction and user operations. These extensions should allow evaluation and prediction not only of effort and costs but also perceptions of psycho-physical serviceability.

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*For further elaboration concerning pavement maintenance model calibration using specific application see Alexander (22) section 9.2.

Obviously much work would be involved in a process involving extension and calibration. However several submodels of user response, construction, damage, etc. (Chapter III) already exist. These could lend much aid to the extension process. The random nature of performance and deterioration and thereby costs should be recognized. Therefore the application of stochastic modeling is suggested as a refinement. The benefits of a total model of this type are far reaching. Not only would more accurate predictions be possible but the extrapolation of the concepts and methodologies would greatly aid the performance and cost investigations concerning many other types of constructed facilities.

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APPENDIX I

Alphabetical Listing of Important Abbreviations

C - coverage; "occurring when each point on the pavement surface has been subjected to one maximum stress by the operating aircraft" (61)

C_{ij} - maintenance equipment fuel consumption factor

CBR - California Bearing Ratio, a measurement of subgrade support capability

CCM_{ij} - hours of j type equipment needed to accomplish one unit of i maintenance operation

CFAIL(I) - coverages to failure for I type aircraft

CP - cracking plus patching, $m^2/1000m^2$

DCBR - design or fall subgrade support value, CBR

DCG - compacted density of finished patch

DOP - average depth of patch placed in centimeters

EF - equivalence factor, converts different type aircraft into an equivalent number of standard or design aircraft

EHN_{ij} - hours of j type equipment needed to accomplish i type maintenance operations for the year

ENVFT - environmental factor; compares variations in subgrade support for fall and spring

ESWL - Equivalent Single Wheel Load

FRF - fraction of ruts filled

FTP - fraction of cracks patched

FTS - fraction of cracks sealed

LOS - length of pavement section, km.

MBA_i - tons of bituminous patching material needed

MP_{ij} - liters of gasoline required for j type

NA - area of cracking on the pavement section, m^2

NA' - new area of cracking after maintenance, m^2

P - wheel load, (single or equivalent single wheel load), pounds

p_c -	tire inflation pressure, kg/cm^2
PT_2 -	efficiency factor, representing hours actually worked for each hour on the job
R -	macro-roughness, cm/km
RCHNG -	change in roughness, cm/km
RD -	mean rut depth, cm
SCBR -	subgrade support, CBR, during spring thaw period
SMP -	square meters of pavement cracking patched
SMS -	square meters of pavement cracking sealed
SPRNG -	number of equivalent coverages during the spring thaw period
SPTHW -	percent of traffic using the pavement during the spring thaw period
TOTAC -	total equivalent coverages for year, not corrected with environmental factors
TRINC -	percent increase in traffic per year
VA -	vertical acceleration, expressed in g's
WOS -	width of pavement section, meters
YTOTL -	total corrected equivalent loadings for year

APPENDIX II

Airfield Pavement Maintenance

USER'S MANUAL

USER'S MANUAL

The User's Manual seeks to not only acquaint the potential user with the computer program but to also enable him to work with it. The following description is structured such that the input data required is defined and explained in terms of quantities and effects. At the end of this appendix is a properly arranged set of input data. This data is the same as the "base run" with the exception that pavement thickness equals 64.01 cms. The execution of this data results in the print out exhibited in Appendix IV.

Data Structure

Maintenance Policy - MAPOL (20)

Format: 4 cards, 5 columns/card, each column F 10.2,
i.e. (5F10.2)

Matrix* Position	Description	Options	Abbreviation in Program
1	drainage maintenance	+1.0, yes; -1.0, no	DSWTH
2	regravel	+1.0, yes; -1.0, no	REGRL
3	shoulder maintenance	" "	SWTCH
4	mow grass medians	" "	VSWTH
5	blade	" "	BLADE
6	frequency of blading (dry)	must be decimal number	FBLDR
7	frequency of blading (wet)	"	FBLWT
8	frequency of mowing/ year	"	FREQM
9	fraction of ruts filled	"	FRF
10	fraction of cracks patched	"	FTP
11	fraction of cracks sealed	"	FTS
12	mean rut depth allowable	"	MRD

---

*Maintenance operation 1-8 are not available in present model option are no, -1.0.

Card Set-Up For Maintenance Policy

Column No.	1	2	3	4	5
Card No.	1 10	11 20	21 30	31 40	41 50
1	-1.0 ①	-1.0 ②	-1.0 ③	-1.0 ④	-1.0 ⑤
2	0.0 ⑥	0.0 ⑦	0.0 ⑧	FRF ⑨	FTP ⑩
3	FTS ⑪	MRD ⑫	0.0 ⑬	0.0 ⑭	0.0 ⑮
4	0.0 ⑯	0.0 ⑰	0.0 ⑱	0.0 ⑲	0.0 ⑳

Matrix Position

MAPOL (13) - (20) unused

Unit Costs Of Maintenance - MUC(25)

Format: 5 cards, 5 columns/card, each column F10.2, i.e. (5F10.2)

Matrix Position	Description	Measure	Abbreviation in Program
1	bituminous distributor	$/hour	UEDS
2	dump truck	$/hour	UEDT
3	tractor loader	$/hour	UELD
4	motor grader	$/hour	UEMG
5	roller	$/hour	UERL
6	water truck 6 cubic meters	$/hour	UETR
7	water truck 7 cubic meters	$/hour	UEWT
8	common labor	$/hour	ULC
9	equipment operator	$/hour	ULEO
10	foreman	$/hour	ULF
11	truck driver	$/hour	ULTD
12	liquid asphalt	$/liter	UMB
13	bituminous plus aggregate patching mix	$/M. Ton	UMBA
14	cover aggregate (sealing)	$/M. Ton	UMCA
15	delivered diesel fuel	$/liter	UMD
16	gravel @ source	$/M. Ton	UMG
17	gasoline	$/liter	UMP
18	water @ source	$/cubic meter	UMW

MUC(19) - (25) unused, 0.0

Card Set Up For Maintenance Unit Costs

Column No.	1	2	3	4	5
Card No.	1 10	11 20	21 30	31 40	41 50
5	UEDS①	UEDT②	UELD③	UEMG④	UERL⑤
6	UETR⑥	UEWT⑦	ULC⑧	ULEO⑨	ULF⑩
7	ULTD⑪	UMB⑫	UMBA⑬	UMCA⑭	UMD⑮
8	UMG⑯	UMP⑰	UMW⑱	0.0⑲	0.0⑳
9	0.0㉑	0.0㉒	0.0㉓	0.0㉔	0.0㉕

Matrix Position

MUC(19) - (25) unused, 0.0

NTYPE, DCBR, T

NTYPE = number of different type aircraft, Integer
DCBR = design CBR, %, Decimal
T = pavement thickness, cm, Decimal

Format; 1 card, 3 columns/card, I10, 2F10.2

	1 10	11 20	21 30	31 40	41 50
Card #10	NTYPE	DCBR	T		

↖— Fill right to left, Integer

Section size; WOS, LOS

WOS = width of runway - meters, Decimal
LOS = length of runway - kilometers, Decimal

Format: 1 card, 2 columns/card, 2F10.2

	1 10	11 20
Card #11	WOS	LOS

Environment - SCBR

SCRB = CBR for spring, %, Decimal

Format: 1 card, 1 column/card, F10.2

	1 10
Card #12	SCBR

Uniform Distribution Parameters - Subroutine UNDIS

Format: 1 card, 5 columns/card, 3F10.2, 2I10

Parameter	Integer	Decimal	Description	Options
SPTHW		X	fraction of yearly traffic during spring thaw	ranges from 0.0 to 1.0 inclusive
TRINC		X	fraction of traffic increase per year	ranges from 0.0 to 1.0 inclusive
TOTAL		X	initialize total no. of accumulated coverages	0.0 if initial year
ITRAF	X		traffic option	0, fraction increase in traffic per year (TRINC) +1, equal traffic each year -1, each year's traffic specified
ITCNT	X		an initialization, determines pattern for uniform distribution of traffic, subroutine UNDIS	-1 or +1 not an initial year 0, initial year

Card #13

1 10	11 20	21 30	31 40	41 50
SPTHW	TRINC	TOTAL	ITRAF	ITCNT

Fill right to left

Discount Rate - DISCR

DISCR = Discount rate (F10.2) expressed as a fraction

Format: 1 card, 1 column/card, F10.2 Decimal

	1 10
Card #14	DISCR

Limits for Time and Vertical Acceleration - NYEAR, SPVA

NYEAR - limiting number of years for evaluation, Integer, I10

SPVA - limiting acceptable average vertical acceleration, Real, F10.2

Format: 1 card, 2 columns/card, I10, F10.2

	1 10	11 20
Card #15	NYEAR	SPVA

Fill this block right to left

Switches for Output Control - ISWTH(5)

Matrix Position	Description of Output	Options
1	detailed accounts of maintenance effort, quantities	+1, output detailed accounts -1 or 0, omit details
2	detailed accounts of maintenance costs	+1, output detailed costs -1 or 0, omit details
3	output the input data	+1, output; -1, 0 omit
4	unused	set equal to 0
5	unused	set equal to 0

Format: 1 card, 5 columns/card, Integer, 5I10

	1 10	11 20	21 30	31 40	41 50
Card #16	ISWTH(1)	ISWTH(2)	ISWTH(3)	ISWTH(4)	ISWTH(5)

Fill all columns right to left

Traffic Data - ITYPE, P, PC, ANUMB

Parameter	Description	Measure	Decimal/Integer
ITYPE	type of aircraft numbered consecutively starting with 1		Integer
P	equivalent single wheel load, ESWL for type aircraft numbered	kg	Decimal
PC	tire inflation pressure	kg/cm^2	Decimal
ANUMB	number of coverages/year for ITYPE aircraft		Decimal

Format: 1 card for each type aircraft, 3 columns/card, I6, 2F10.2

Card #17

1 6	7 16	17 26
ITYPE	P	PC

Fill right to left

.
.
.

Format: 1 card for each type aircraft, 2 columns/card, I6,F10.2

Card # NTYPE +16 +1

1 6	7 16
ITYPE	ANUMB

Fill right to left

.
.
.

End

Data Set-Up For Base Run With T - 64.01 cm

Column No.	1 10	11 20	21 30	31 40	41 50
Card No.	1	2	3	4	5
1	-1.0	-1.0	-1.0	-1.0	-1.0
2	0.0	0.0	0.0	0.0	0.3
3	0.3	2.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	4.00	3.00	3.00	3.57	4.10
6	0.0	0.0	5.25	7.17	8.20
7	6.68	0.04	6.60	3.45	0.04
8	3.58	0.07	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0
10	6	10.0	64.01		
11	45.75	3.05			
12	7.0				
13	0.20	0.10	0.0	0	0
14	0.07				
15	20	0.7			
16	-1	-1	+1	0	0

Column No.	1 6	7 16	17 26
Card No.	1	2	3
17	1	28636.63	10.57
18	2	30909.09	11.63
19	3	30909.09	11.63
20	4	15909.09	9.16
21	5	18181.82	10.15
22	6	41818.18	12.68
23	1	100.0	
24	2	100.0	

Column No.	1 6	7 16	17 26
Card No.	1	2	3
25	3	100.0	
26	4	100.0	
27	5	100.0	
28	6	100.0	

APPENDIX III

Airfield Pavement Maintenance

Computer Program Listing

```
C     THIS IS THE CONTROLLING PORTION OF THE AIRFIELD PAVEMENT MAINTENANCE
C     PROGRAM
C
C                                 MAIN
C
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C
C
C
C     BEGIN EVALUATION
C
C
C     INPUT - OUTPUT CONTROL
      IIN=5
      IOUT=6
C
C     VARIABLES REQUIRED FOR RUFIN
C
      PRUFF=79.0
C
C     VARIABLES REQUIRED FOR MAINT
C
      PRECP=0.
      PRERD=0.
C
C     VARIABLES REQUIRED FOR PWCAC
C
      DO 9901 I=1,4
      AMTCT(I)=0.
```

```
      APWC(I)=0.
 9901 CONTINUE
C
      CALL DATA
      CALL EQUIV
      CALL ENVIR
      IYEAR=0
 5001 IYEAR=IYEAR+1
      WRITE (IOUT,71) IYEAR
 71   FORMAT (1H1,120('*'),///,54X,'YEAR =',I6,//)
      CALL UNDIS
      CALL RUFIN
      CALL DETER
      CALL MAINT
      CALL COSTS
      CALL PWCAC
      CALL IMPRU
C
C
C     CHECK FO EXCESSIVE  1 VERTICAL ACCELERATION
C                          2 END OF TEST PERIOD
      IF (SPVA-VA) 2501,2501,2502
 2501 GO TO 7777
 2502 IF (NYEAR-IYEAR) 2501,2501,5001
 7777 CONTINUE
      CALL EXIT
      END
```

```
      SUBROUTINE DATA
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C
C     MAINTENANCE POLICY
      READ (IIN,101) (MAPOL(I),I=1,20)
101   FORMAT (5F10.2)
C
C     UNIT COSTS, MUC, FOR MAINTENANCE
C
      READ (IIN,102) (MUC(I),I=1,25)
102   FORMAT (5F10.2)
C
C     VARIABLES REQUIRED FOR EQUIV
C
      READ (IIN,103) NTYPE,DCBR,T
103   FORMAT (I10,2F10.2)
C
C     SECTION SIZE
C
      READ (IIN,104) WOS,LOS
104   FORMAT (2F10.2)
C
C     VARIABLES REQUIRED FOR ENVIR
C
      READ (IIN,105) SCBR
105   FORMAT (F10.2)
C
C     VARIABLES REQUIRED FOR UNDIS
C
```

```
      READ (IIN,106) SPTHW,TRINC,TOTAL,ITRAF,ITCNT                      DATA0037
  106 FORMAT (3F10.2,2I10)                                              DATA0038
C     DISCR, DISCOUNT RATE                                              DATA0039
      READ (IIN,107) DISCR                                              DATA0040
  107 FORMAT (F10.2)                                                    DATA0041
C                                                                       DATA0042
C     LIMITS FOR TIME AND VERTICAL ACCELERATION                         DATA0043
C                                                                       DATA0044
      READ (IIN,108) NYEAR,SPVA                                         DATA0045
  108 FORMAT (I10,F10.2)                                                DATA0046
C     SWITCHES FOR OUTPUT CONTROL                                       DATA0047
C          ISWTH(1)=+1, OUTPUT DETAILED ACCOUNTS OF MAINT               DATA0048
C                  -1 OR 0, OMIT DETAILS                                DATA0049
C                                                                       DATA0050
C          ISWTH(2)=+1, OUTPUT DETAILED MAINT. COSTS                    DATA0051
C                  -1 OR 0, OMIT DETAILS                                DATA0052
C                                                                       DATA0053
      READ (IIN,109) (ISWTH(I),I=1,5)                                   DATA0054
  109 FORMAT (5I10)                                                     DATA0055
      IF (ISWTH(3)) 301,301,300                                         DATA0056
  300 CONTINUE                                                          DATA0057
      WRITE (IOUT,200)                                                  DATA0058
  200 FORMAT (1H1,120('*'),///,40X,' INPUT DATA, INCLUSIVE OF TRAFFIC IN DATA0059
     1PUT',///,120('*'))                                                DATA0060
      WRITE (IOUT,201)                                                  DATA0061
  201 FORMAT (1H0,' MAINTENANCE POLICY')                                DATA0062
      WRITE (IOUT,202) (MAPOL(I),I=1,20)                                DATA0063
  202 FORMAT (1H0,5(F10.2,10X))                                         DATA0064
      WRITE (IOUT,203)                                                  DATA0065
  203 FORMAT (1H0,' UNIT COSTS FOR MAINTENANCE')                        DATA0066
      WRITE (IOUT,204) (MUC(I),I=1,25)                                  DATA0067
  204 FORMAT (1H0,5(F10.2,10X))                                         DATA0068
      WRITE (IOUT,205) NTYPE,DCBR,T                                     DATA0069
  205 FORMAT (1H0,' NTYPE =',I10,5X,' DCBR =',F10.2,5X,' T =',F10.2)    DATA0070
      WRITE (IOUT,206) WOS,LOS                                          DATA0071
  206 FORMAT (1H0,' WOS =',F10.2,10X,' LOS =',F10.2)                    DATA0072
```

```
      WRITE (IOUT,207)                                                  DATA0073
  207 FORMAT (1H0,' SCBR',14X,'SPTHW',11X,'TRINC',10X,'TOTAL',12X,'ITRAF DATA0074
     1',11X,'ITCNT')                                                    DATA0075
      WRITE (IOUT,208) SCBR,SPTHW,TRINC,TOTAL,ITRAF,ITCNT               DATA0076
  208 FORMAT (1H ,4(F10.2,5X),2(I10,5X))                                DATA0077
      WRITE (IOUT,209)                                                  DATA0078
  209 FORMAT (1H0,5X,'DISCR',11X,'NYEAR',11X,'SPVA')                    DATA0079
      WRITE (IOUT,210) DISCR,NYEAR,SPVA                                 DATA0080
  210 FORMAT (1H ,F10.2,5X,I10,5X,F10.2)                                DATA0081
      WRITE (IOUT,211) (ISWTH(I),I=1,5)                                 DATA0082
  211 FORMAT (1H0,' OUTPUT SWITCH STATUS',5I10)                         DATA0083
  301 CONTINUE                                                          DATA0084
      RETURN                                                            DATA0085
      END                                                               DATA0086
```

```
      SUBROUTINE EQUIV                                                  EQUI0001
      REAL MAPOL,MUC,MTCT,LOS,WOS                                       EQUI0002
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)             EQUI0003
      DIMENSION APWC(4),AMTCT(4),PWC(4)                                 EQUI0004
      DIMENSION ISWTH(5)                                                EQUI0005
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAFEQUI0006
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD, EQUI0007
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR                            EQUI0008
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH                     EQUI0009
C     THIS SUBROUTINE CALCULATES COVERAGES AND LOADING WEIGHTING FACTORS EQUI0010
C     VARIABLES CONSIDERED ARE:                                         EQUI0011
C           1. DESIGN CBR OF SUBGRADE, DCBR                             EQUI0012
C           2. P EQUIVALENT SINGLE WHEEL LOAD OF SPECIFIC AIRCRAFT      EQUI0013
C           3. PC TIRE INFLATION PRESSURE                               EQUI0014
C           4. CFAIL(I), COVERAGES TO FAILURE FOR AIRCRAFT, I           EQUI0015
C                                                                       EQUI0016
C                                                                       EQUI0017
C     WRITE OUT   NO. OF DIFFERENT TYPE AIRCRAFT TO BE CONSIDERED       EQUI0018
      WRITE (IOUT,401) NTYPE                                            EQUI0019
  401 FORMAT (1H ,'NTYPE  =',I6)                                        EQUI0020
C     LOOP TO CALCULATE CFAIL FOR EACH AIRCRAFT,I                       EQUI0021
      WRITE (IOUT,402)                                                  EQUI0022
  402 FORMAT (1H ,'  ITYPE',9X,'P',14X,'PC',15X,'T',12X,'DCBR')         EQUI0023
C     CONVERT CM. TO INCHES                                             EQUI0024
      T=T/2.54                                                          EQUI0025
      DO 801 I=1,NTYPE                                                  EQUI0026
      READ (IIN,102) ITYPE,P,PC                                         EQUI0027
  102 FORMAT (I6,2F10.2)                                                EQUI0028
      WRITE (IOUT,502) ITYPE,P,PC,T,DCBR                                EQUI0029
  502 FORMAT (1H ,I6,4X,F10.2,4X,F10.2,4X,F10.2,4X,F10.2)               EQUI0030
C     CONVERT KILOGRAMS TO POUNDS                                       EQUI0031
      P=2.2*P                                                           EQUI0032
C     CONVERT KILOGRAMS / SQUARE CM. TO PSI                             EQUI0033
      PC=14.19*PC                                                       EQUI0034
      RTAIR=((P/(8.1*DCBR))-(P/(PC*3.1416)))**0.5                       EQUI0035
      CFAIL(I)=10.**(((T/RTAIR)-0.15)/0.23)                             EQUI0036
```

```
801    CONTINUE                                                         EQUI0037
C      LOOP TO CALCULATE EQUIVALENCE FACTORS                            EQUI0038
       DO 802 I=1,NTYPE                                                 EQUI0039
       EF(I)=CFAIL(1)/CFAIL(I)                                          EQUI0040
802    CONTINUE                                                         EQUI0041
       WRITE (IOUT,403)                                                 EQUI0042
403    FORMAT (1H ,'CFAIL')                                             EQUI0043
       WRITE (IOUT,503) (CFAIL(I),I=1,NTYPE)                            EQUI0044
503    FORMAT (1H ,F10.2)                                               EQUI0045
       WRITE (IOUT,404)                                                 EQUI0046
404    FORMAT (1H ,' EQUIVALENCE FACTORS')                              EQUI0047
       WRITE (IOUT,405) (EF(I),I=1,NTYPE)                               EQUI0048
405    FORMAT (1H ,F10.2)                                               EQUI0049
       RETURN                                                           EQUI0050
       END                                                              EQUI0051
```

```
      SUBROUTINE ENVIR                                                  ENVI0001
      REAL MAPOL,MUC,MTCT,LOS,WOS                                       ENVI0002
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)             ENVI0003
      DIMENSION APWC(4),AMTCT(4),PWC(4)                                 ENVI0004
      DIMENSION ISWTH(5)                                                ENVI0005
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF ENVI0006
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD, ENVI0007
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR                            ENVI0008
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH                     ENVI0009
C     ENFCT CALCULATES ENVIRONMENTAL FACTOR                             ENVI0010
C     FOR DETERIORATION DURING SPRING THAW                              ENVI0011
C            1. DCBR, DESIGN CBR                                        ENVI0012
C            2. SCBR, SPRING CBR                                        ENVI0013
C            3. ENVFT, ENVIRONMENTAL FACTOR                             ENVI0014
      ENVFT=ALOG10(DCBR)/ALOG10(SCBR)                                   ENVI0015
      WRITE (IOUT,406) ENVFT                                            ENVI0016
406   FORMAT (1H ,' ENVFT =',F6.2)                                      ENVI0017
      WRITE (IOUT,407) DCBR,SCBR                                        ENVI0018
407   FORMAT (1H ,' DCBR =',F6.2,5X,' SCBR =',F6.2)                     ENVI0019
      RETURN                                                            ENVI0020
      END                                                               ENVI0021
```

```
      SUBROUTINE UNDIS                                                  UNDI0001
      REAL MAPOL,MUC,MTCT,LOS,WOS                                       UNDI0002
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)             UNDI0003
      DIMENSION APWC(4),AMTCT(4),PWC(4)                                 UNDI0004
      DIMENSION ISWTH(5)                                                UNDI0005
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF UNDI0006
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD, UNDI0007
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR                            UNDI0008
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH                     UNDI0009
C                                                                       UNDI0010
C                                                                       UNDI0011
C                                                                       UNDI0012
C     UNDIS CALCULATES UNIFORM DISTRIBUTED COVERAGES FOR A PERIOD OF ONE UNDI0013
C     YEAR                                                              UNDI0014
C                                                                       UNDI0015
C     THREE OPTIONS ARE AVAILABLE                                       UNDI0016
C           1. ITRAF = 1, EQUAL TRAFFIC EACH YEAR                       UNDI0017
C     2. ITRAF = 0, TRINC (%),% INCREASE IN TRAFFIC EACH YEAR           UNDI0018
C           3. ITRAF = -1, EACH YEARS TRAFFIC SPECIFIED                 UNDI0019
C                                                                       UNDI0020
C                                                                       UNDI0021
C     CHECK FOR INITIAL YEAR, ITCNT=0                                   UNDI0022
      IF (ITCNT) 2002,2001,2002                                         UNDI0023
C     2002 IMPLIES THIS IS NOT AN INITIAL YEAR OF ANALYSIS              UNDI0024
C     CHECK FOR TRAFFIC OPTION; ITRAF=-1,0,1                            UNDI0025
 2002 IF (ITRAF) 2001,2003,2004                                         UNDI0026
 2003 YTOTL = YTOTL + YTOTL*TRINC                                       UNDI0027
      WRITE (IOUT,412) YTOTL                                            UNDI0028
 412  FORMAT (1H ,'TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =',F10. UNDI0029
     12)                                                                UNDI0030
      GO TO 2004                                                        UNDI0031
C     2001 STARTS UNIFORM DISTRIBUTION ANALYSIS FOR INITIAL OR ITRAF=-1 UNDI0032
 2001 TOTAC=0.                                                          UNDI0033
C     LOOP FOR UNIFORM COVERAGES; NO ENVIRONMENTAL WEIGHTING            UNDI0034
      WRITE (IOUT,408) NTYPE                                            UNDI0035
 408  FORMAT (1H ,' NTYPE =',I6,//)                                     UNDI0036
```

```
      WRITE (IOUT,409)                                                  UNDI0037
  409 FORMAT (1H ,'TYPE AIRCRAFT',4X,'NO. COVERAGES',4X,'EQUIV. COVER') UNDI0038
      DO 803 J=1,NTYPE                                                  UNDI0039
C     READ TYPE OF AIRCRAFT AND NO. OF COVERAGES                        UNDI0040
      READ (IIN,103) ITYPE,ANUMB                                        UNDI0041
  103 FORMAT (I6,F10.2)                                                 UNDI0042
C     CALCULATE EQUIVALENT UNIFORM COVERAGES FOR THIS AIRCRAFT          UNDI0043
      UNIFA=ANUMB*EF(ITYPE)                                             UNDI0044
      WRITE (IOUT,509) ITYPE,ANUMB,UNIFA                                UNDI0045
  509 FORMAT (1H ,I6,12X,F10.2,7X,F10.2)                                UNDI0046
C     ACCUMULATE UNIFORM COVERAGES                                      UNDI0047
      TOTAC=TOTAC+UNIFA                                                 UNDI0048
  803 CONTINUE                                                          UNDI0049
      WRITE (IOUT,411) TOTAC                                            UNDI0050
  411 FORMAT (1H ,' TOTAL EQUIVALENT COVERAGES FOR YEAR =',F10.2)       UNDI0051
C     DETERMINE NUMBER OF EQUIVALENT COVERAGES DURING SPRING THAW       UNDI0052
      SPRNG=TOTAC*SPTHW                                                 UNDI0053
C     GET TOTAL CORRECTED EQUIVALENT LOADINS FOR YEAR; INCLUDE          UNDI0054
C     ENVIRONMENTAL FACTOR                                              UNDI0055
      YTOTL=(TOTAC-SPRNG)+(SPRNG*ENVFT)                                 UNDI0056
      WRITE (IOUT,413) YTOTL                                            UNDI0057
  413 FORMAT (1H ,' TOTAL UNIFORM COVERAGES, SAME OR REFEED,= ',F10.2)  UNDI0058
C     UPDATE ITCNT; CK. ON INITIAL YEAR                                 UNDI0059
 2004 ITCNT=ITCNT+1                                                     UNDI0060
      TOTAL=TOTAL+YTOTL                                                 UNDI0061
      WRITE (IOUT,414) TOTAL                                            UNDI0062
  414 FORMAT (1H ,' ACCUMULATED COVERAGES =',F16.2)                     UNDI0063
      RETURN                                                            UNDI0064
      END                                                               UNDI0065
```

```
      SUBROUTINE RUFIN
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C     DETERMINE CHANGE IN ROUGHNESS FOR YEAR, (CM/KM)
      RCHNG=(YTOTL/CFAIL(1))*158
C     CALCULATE ROUGHNESS
      RUFF=PRUFF+RCHNG
      WRITE (IOUT,414) RCHNG,RUFF,PRUFF
 414  FORMAT (1H ,' RCHNG =',F10.2,5X,' RUFF =',F10.2,5X,' PRUFF =',F10.
     12)
      RUFF1=PRUFF
      RUFF2=RUFF
      RETURN
      END
```

```
      SUBROUTINE DETER
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C
C
C     DETER ESTIMATES CRACKING AND PATCHING AND MEAN RUT DEPTH AS A
C     FUNCTION OF ROUGHNESS
C
C     CALCULATE (C+P); SQUARE METERS /1000 SQUARE METERS
      CP=-627.9+89*((0.633*RUFF)**0.5)
      IF (CP) 9801,9801,9802
 9801 CP=0.
 9802 CONTINUE
C     CALCULATE RD; CENTIMETERS
      RD=-26.7+0.338*RUFF+0.335*((CP)**0.5)
      IF (RD) 9803,9803,9804
 9803 RD=0.
 9804 CONTINUE
      WRITE (IOUT,416) CP,RD
  416 FORMAT (1H ,' C+P,BEFORE MAINTENANCE =',F10.2,5X,' RD,BEFORE MAINT
     1ENANCE =',F10.2)
      RETURN
      END
```

```
      SUBROUTINE MAINT
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C
C
C
C     MAINT PERFORMS MAINTENANCE ON CP AND RD AS PRESCRIBED IN
C     MAINTENANCE POLICY
      FRF=MAPOL(9)
      FTP=MAPOL(10)
      FTS=MAPOL(11)
      MRD=MAPOL(12)
C
C     DELCP,INCREASE CP;PRECP,PREVIOUS CP
C
      DELCP=CP*WOS-PRECP
C
C     DELRD;INCREASE RD;PRERD,PREVIOUS RD
C
      DELRD=RD-PRERD
C
C     SQUARE METERS PATCHED,SMP
      SMP=FTP*DELCP
C     SQUARE METERS SEALED,SMS
      SMS=FTS*DELCP
C     CHECK POLICY FOR RUT DEPTH MAINT.
      IF (RD-MRD) 2010,2010,2011
C     ESTIMATE CMPR=VOL. OF MATERIAL FOR FILLING
C              FIXRD= FIX RUT DEPTH
2010  CMPR=0.
```

```
      FIXRD=0.
      GO TO 2012
 2011 CMPR=467.*FRF*RD
      FIXRD=0.5*FRF*RD
 2012 CONTINUE
C     ESTIMATE CHANGED CP AND RD AFTER MAINTENANCE FOR YEAR
      PRECP=CP*WOS-(SMP+SMS)
      IF (PRECP) 501,501,502
  501 PRECP=0.
  502 CONTINUE
      PRERD=RD-FIXRD
      CPNEW=PRECP/WOS
      WRITE (IOUT,417) CPNEW,PRERD
 417  FORMAT (1H ,' CRACKING AND PATCHING, AFTER MAINTENANCE =',F10.2,5X
     1,' RUT DEPTH AFTER MAINTENANCE =',F10.2)
      WRITE (IOUT,418)
 418  FORMAT (1H ,5X,'DELCP',5X,'DELRD',5X,'SMP',7X,'SMS',7X,'CMPR',6X,'
     1FIXRD',5X,'FTP',7X,'FTS',7X)
      WRITE (IOUT,419) DELCP,DELRD,SMP,SMS,CMPR,FIXRD,FTP,FTS
 419  FORMAT (1H ,8F10.2)
      RETURN
      END
```

```
      SUBROUTINE COSTS
      REAL MAPOL(20)
      REAL KMCA,KMAT,KLABR,KEQ,KLEM
      REAL KEMG,KEWT,KERL,KEDT,KELD,KETR,KEDS,KLC,KLTD,KLEO,KLF,KMG,
     1 KMW,KMBA,KMP,KMD,KMB
      REAL MRD
      REAL EHN(12,7), LC(12,7), LEO(12,7), LF(12,7), LTD(12,7),
     1 MB(12,7), MBA(12,7), MCA(12,7), MD(12,7), MG(12,7), MP(12,7),
     2 MW(12,7),LG(12,7)
      REAL LOS,WOS
      REAL MTCT(25), MUC(25)
      DIMENSION CFAIL(20),EF(20)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C     PATCHING OPERATION CONSUMPTION
      DATA CCM1,CCM2/7.,3./
C     DISTRIBUTOR CONSUMPTION
      DATA CD1,CD2/7.,1./
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 CLG1,CLG2/1.,1./
C     ROLLER CONSUMPTION
      DATA CR1,CR2/5.,1./
C     RUT PATCHING CONSUMPTION
      DATA CRF1,CRF2,CRF3,CRF4,CRF5/1.,.7,.25,.2,.2/
C     SEALING OPERATION CONSUMPTION
      DATA CS1,CS2,CS3,CS4/1.4,1.4,.4,.3/
```

```
C       DUMP TRUCK CONSUMPTION
        DATA CT1,CT2/7.,1./
C       WATER TRUCK CONSUMPTION
        DATA CWT1,CWT2/0.,0./
C       MOWER CONSUMPTIONS
        DATA CV1,CV2/0.,0./
C       DENSITY OF COMPACTED GRAVEL
        DATA DCG/2.24/
C       DENSITY OF LOOSE GRAVEL
        DATA DLG/1.8/
C       AVERAGE DEPTH OF PATCHES (CM.)
        DATA DOP/5./
C       LABOR EFFICIENCY
        DATA PCL/.75/
C       DISTRIBUTOR PRODUCTION
        DATA PD2/.75/
C       MOTOR GRADER PRODUCTION
        DATA PMG1,PMG2,PMG3/2.4,.75 ,6.0/
C       LOADER PRODUCTION
        DATA PL1,PL2/30.,.75/
C       ROLLER PRODUCTION
        DATA PR1,PR2,PR3,PR4,PR5/2.,.75,6.,3.,5./
C       DUMP TRUCK PRODUCTION
        DATA PT1,PT2,PT3,PT4,PT5,PT6/3.,.75,40.,5.,2.,5./
C       MOWER PRODUCTIVITIES
        DATA PV1,PV2,PV3/0.,0.,0./
C       WATER TRUCK PRODUCTION
        DATA PWT1,PWT2,PWT3,PWT4,PWT5,PWT6,PWT7/7*0./
C       AGGREGATE RATE FOR SEAL ( K./ SQ. METERS)
        DATA SA/14./
C       ASPHALT RATE FOR SEAL (LITERS/ SQ. METER)
        DATA SB/1.2/
        IPRNT=IOUT
C
C
C       INITIALIZE COST MATRICES
```

```
      DO 290 I= 1,12                                                    COST 730
      DO 291 J = 1,7                                                    COST 740
       EHN(I,J)= 0.                                                     COST 750
        LC(I,J)= 0.                                                     COST 760
       LEO(I,J)= 0.                                                     COST 770
       LF (I,J)= 0.                                                     COST 780
      LG(I,J) = 0.                                                      COST 790
       LTD(I,J)= 0.                                                     COST 800
        MB(I,J)= 0.                                                     COST 810
       MBA(I,J)= 0.                                                     COST 820
      MCA(I,J)=0                                                        COST 830
        MD(I,J)= 0.                                                     COST 840
        MG(I,J)= 0.                                                     COST 850
        MP(I,J)= 0.                                                     COST 860
      MW(I,J) = 0.                                                      COST 870
  291 CONTINUE                                                          COST 880
  290 CONTINUE                                                          COST 890
       DO 2931 I = 1,25                                                 COST 900
 2931  MTCT(I) = 0.                                                     COST 910
C     UNIT PRICES                                                       COST 920
      UEDS=MUC(1)                                                       COST 930
      UEDT=MUC(2)                                                       COST 940
      UELD=MUC(3)                                                       COST 950
      UEMG=MUC(4)                                                       COST 960
      UERL=MUC(5)                                                       COST 970
      UETR=MUC(6)                                                       COST 980
      UEWT=MUC(7)                                                       COST 990
      ULC=MUC(8)                                                        COST1000
      ULEO = MUC(9)                                                     COST1010
      ULF=MUC(10)                                                       COST1020
      ULTD=MUC(11)                                                      COST1030
      UMB=MUC(12)                                                       COST1040
      UMBA=MUC(13)                                                      COST1050
      UMCA=MUC(14)                                                      COST1060
      UMD=MUC(15)                                                       COST1070
      UMG=MUC(16)                                                       COST1080
```

```
      UMP=MUC(17)                                                       COST1090
      UMW=MUC(18)                                                       COST1100
124   CONTINUE                                                          COST1110
C                                                                       COST1120
C                                                                       COST1130
C     MAINTENANCE POLICY                                                COST1140
      DSWTH=MAPOL(1)                                                    COST1150
      REGRL=MAPOL(2)                                                    COST1160
      SWTCH=MAPOL(3)                                                    COST1170
      VSWTH=MAPOL(4)                                                    COST1180
      BLADE=MAPOL(5)                                                    COST1190
      FBLDR=MAPOL(6)                                                    COST1200
      FBLWT=MAPOL(7)                                                    COST1210
      FREQM=MAPOL(8)                                                    COST1220
      FRF=MAPOL(9)                                                      COST1230
      FTP=MAPOL(10)                                                     COST1240
      FTS=MAPOL(11)                                                     COST1250
      MRD=MAPOL(12)                                                     COST1260
      DISCM=4.0                                                         COST1270
      DISG=4.0                                                          COST1280
      DISW=0.0                                                          COST1290
CC    COMPUTATION OF LABOR,EQUIPMENT AND MATERIAL REQUIRED FOR          COST1300
C      PAVEMENT MAINTENANCE                                             COST1310
CC    OPERATION   PLACE AND COMPACT BITUMINOUS PATCHING                 COST1320
C     OF COLD MIX AS DEEP OR SKIN PATCHES                               COST1330
      EHN(6,4)=CCM2*DOP/PT2 *SMP*.01                                    COST1340
C     COMMON LABOR NEEDED                                               COST1350
      LC(6,4)=CCM1*DOP/PCL *SMP*.01                                     COST1360
C     TRUCK DRIVER                                                      COST1370
      LTD(6,4) = EHN(6,4)*CT2                                           COST1380
C     FUEL REQUIRED                                                     COST1390
      MP(6,4)= EHN(6,4)*CT1                                             COST1400
CC    OPERATION  HAUL COLD MIX TO ROAD SECTION                          COST1410
C     TIME NEEDED FOR 1ROUND TRIP                                       COST1420
      RT=PT4+PT6+DISCM*60.*2./PT3                                       COST1430
C     TRUCK HRS. NEEDED TO HAUL PATCHING MIX FOR ONE KILOMETER OF ROAD  COST1440
```

```
      EHN(7,4)=DCG*RT*DOP/(DLG*PT1*60*PT2)  *SMP*.01                    COST1450
C     TRUCK DRIVER HOURS                                                COST1460
      LTD(7,4) = EHN(7,4)*CT2                                           COST1470
C     FUEL REQUIRED                                                     COST1480
      MP(7,4) = EHN(7,4)*CT1                                            COST1490
CC    OPERATION  LOAD COLD MIX INTO TRUCKS                              COST1500
C     LOADER TIME                                                       COST1510
      EHN(7,5) = DCG*DOP/(PL1*PL2*DLG) *SMP*.01                         COST1520
C     OPERATOR TIME                                                     COST1530
      LEO(7,5) = EHN(7,5)*CL2                                           COST1540
C     FUEL                                                              COST1550
       MD(7,5) = EHN(7,5)*CL1                                           COST1560
C     PREMIXED PATCHING MATERIAL USED                                   COST1570
      MBA(6,4)=DCG*DOP *SMP*.01                                         COST1580
CC    OPERATION PLACE AND ROLL BIT. SEAL COAT FOR ONE KILOMETER OF ROAD COST1590
C     COMMON LABOR REQUIRED                                             COST1600
      LC(8,4)=CS1/PCL    *SMS*.01                                       COST1610
      EHN(8,4)=CS2/PT2 *SMS*.01                                         COST1620
C     TRUCK DRIVER                                                      COST1630
      LTD(8,4) = EHN(8,4)*CT2                                           COST1640
C     DISTRIBUTOR REQUIRED                                              COST1650
      EHN(8,7)= CS3/PD2    *SMS*.01                                     COST1660
C     DISTRIBUTOR TRUCK DRIVER                                          COST1670
      LTD(8,7) = EHN(8,7)*CD2                                           COST1680
C     ROLLER HOURS                                                      COST1690
      EHN(8,3)=CS4/PR2 *SMS*.01                                         COST1700
C     ROLLER OPERATER                                                   COST1710
      LEO(8,3) = EHN(8,3)*CR2                                           COST1720
C     FUEL FOR TRUCKS, DISTRIBUTOR, ROLLER                              COST1730
      MP(8,4) = EHN(8,4)*CT1                                            COST1740
      MP(8,7) = EHN(8,7)*CD1                                            COST1750
      MP(8,3) = EHN(8,3)*CR1                                            COST1760
CC    OPERATION  TRANSPORT AGGREGATE FROM SOURCE TO ROAD SECTION        COST1770
C     DUMP TRUCK TIME TO MAKE ONE ROUND TRIP                            COST1780
      RT=PT4+PT6+DISCM*60*2/PT3                                         COST1790
C     HOURS NEEDED FOR SEALING ON ONE KILOMETER OF ROAD                 COST1800
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```
      EHN(9,4)=SA*100*RT/(DLG*PT1*60*1000.)*SMS*.01                     COST1810
C     DRIVER TIME                                                       COST1820
      LTD(9,4) = EHN(9,4)*CT2                                           COST1830
C     LOADER TIME                                                       COST1840
      EHN(9,5)=SA* .1 /(DLG*PL1)* SMS * .01                             COST1850
C     LOADER OPERATOR                                                   COST1860
      LEO(9,5)= EHN(9,5)*CL2                                            COST1870
C     MATERIAL                                                          COST1880
C     FUEL                                                              COST1890
       MP(9,4) = EHN(9,4)*CT1                                           COST1900
      MP(9,5) = EHN(9,5)*CL1                                            COST1910
C     AGGREGATE                                                         COST1920
      MCA(8,4)=.1*SA  *SMS*.01                                          COST1930
C     LIQUID ASPHALT                                                    COST1940
      MB(8,4) = SB*SMS                                                  COST1950
CC    OPERATION; PLACE AND COMPACT RUT PATCHING MIX PER KILOMETER       COST1960
C     COMMON LABOR                                                      COST1970
      LC(10,4)=CRF1/PCL *CMPR                                           COST1980
C     DUMP TRUCK                                                        COST1990
      EHN(10,4)=CRF2/PT2*CMPR                                           COST2000
C     TRUCK DRIVER                                                      COST2010
      LTD(10,4)  = EHN(10,4)*CT2                                        COST2020
C     FUEL                                                              COST2030
      MP(10,4) = EHN(10,4)*CT1                                          COST2040
C     MOTOR GRADER                                                      COST2050
      EHN(10,1)=CRF3/PMG2*CMPR                                          COST2060
C     MOTOR GRADER OPERATOR                                             COST2070
      LEO(10,1) = EHN(10,1)*CMG2                                        COST2080
C     FUEL                                                              COST2090
      MD(10,1) = EHN(10,1) *CMG1                                        COST2100
C     DISTRIBUTOR                                                       COST2110
      EHN(10,7)=CRF5/PD2*CMPR                                           COST2120
C     DISTRIBUTOR TRUCK DRIVER                                          COST2130
      LTD(10,7) = EHN(10,7) *CD2                                        COST2140
C     FUEL                                                              COST2150
      MP(10,7) = EHN(10,7)* CD1                                         COST2160
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C     ROLLER                                                            COST2170
      EHN(10,3)=CRF4/PR2 *CMPR                                          COST2180
C     OPERATOR                                                          COST2190
      LEO(10,3) = EHN(10,3)*CR2                                         COST2200
C     FUEL                                                              COST2210
      MP(10,3) = EHN(10,3) *CR1                                         COST2220
C     PATCHING MIXTURE                                                  COST2230
      MBA(10,4)=DCG*CMPR                                                COST2240
CC    TRANSPORT PATCHING MIXTURE FOR RUTS/                              COST2250
C     TIME FOR ONE ROUND TRIP                                           COST2260
      RT=PT4+PT6+DISCM*60*2/PT3                                         COST2270
C     TRUCK TIME                                                        COST2280
      EHN(11,4)=DCG*RT/(DLG*PT1*PT2*60)*CMPR                            COST2290
C     TRUCK DRIVER                                                      COST2300
      LTD(11,4) = EHN(11,4)*CT2                                         COST2310
C     FUEL                                                              COST2320
      MP(11,4) = EHN(11,4)*CT1                                          COST2330
138   CONTINUE                                                          COST2340
C     LOADER                                                            COST2350
      EHN(11,5) = DCG/(DLG*PL1*PL2)*CMPR                                COST2360
C     LOADER OPERATOR                                                   COST2370
      LEO(11,5) = EHN(11,5)*CL2                                         COST2380
C     FUEL                                                              COST2390
      MD(11,5) = EHN(11,5)*CL1                                          COST2400
C                                                                       COST2410
458   CONTINUE                                                          COST2420
CCC    COST SUM SECTION                                                 COST2430
C     ALL MAINTENANCE COSTS HAVE BEEN CALCULATED AT THIS POINT          COST2440
C     THE COSTS WILL NOW BE SUMMED AND THESE SUMS WILL BE               COST2450
C     RETURNED TO THE MAIN PROGRAM                                      COST2460
C                                                                       COST2470
C     COST PER KM                                                       COST2480
C     INITIALIZE COST SUM MATRIX                                        COST2490
C     SXYZ = QUANTITIES OF XYZ PER KM PER YEAR                          COST2500
C     MOTORGRADER                                                       COST2510
      SEMG= 0.                                                          COST2520
```

```
139   CONTINUE                                                          COST2530
C     WATER TRUCK                                                       COST2540
      SEWT = 0.                                                         COST2550
C     ROLLER                                                            COST2560
      SERL  =  0.                                                       COST2570
C     DUMP TRUCK                                                        COST2580
      SEDT  =  0.                                                       COST2590
      SELD  =  0.                                                       COST2600
C     TRACTOR AND MOWER HOURS                                           COST2610
      SETR  =  0.                                                       COST2620
C     DISTRIBUTOR                                                       COST2630
140   CONTINUE                                                          COST2640
      SEDS  =  0.                                                       COST2650
       SLC = 0.                                                         COST2660
       SLEO = 0.                                                        COST2670
      SLF = 0.                                                          COST2680
      SLG = 0.                                                          COST2690
       SLTD =0.                                                         COST2700
      SMB = 0.                                                          COST2710
      SMBA = 0.                                                         COST2720
      SMCA = 0.                                                         COST2730
       SMD = 0.                                                         COST2740
       SMG = 0.                                                         COST2750
      SMP = 0.                                                          COST2760
C     LOADER                                                            COST2770
      SMW = 0.                                                          COST2780
      DO 301 I = 1,12                                                   COST2790
      DO 300 J = 1,7                                                    COST2800
      SLC = SLC +LC(I,J)                                                COST2810
      SLEO = SLEO + LEO(I,J)                                            COST2820
      SLF = SLF +LF(I,J)                                                COST2830
      SLG = SLG+ LG(I,J)                                                COST2840
      SLTD = SLTD + LTD(I,J)                                            COST2850
      SMB= SMB + MB(I,J)                                                COST2860
      SMBA = SMBA + MBA(I,J)                                            COST2870
      SMCA = SMCA +MCA(I,J)                                             COST2880
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```
      SMD = SMD + MD(I,J)                                                COST2890
      SMG = SMG + MG(I,J)                                                COST2900
      SMP = SMP + MP(I,J)                                                COST2910
       SMW = SMW + MW (I,J)                                              COST2920
  300 .CONTINUE                                                          COST2930
  301 CONTINUE                                                           COST2940
  C                                                                      COST2950
      DO 380 I = 1,12                                                    COST2960
      J =  1                                                             COST2970
      SEMG = SEMG + EHN(I,J)                                             COST2980
      J =  2                                                             COST2990
      SEWT = SEWT+ EHN(I,J)                                              COST3000
      J =  3                                                             COST3010
      SERL  =  SERL  +EHN(I,J)                                           COST3020
      J =  4                                                             COST3030
      SEDT  = SEDT   +EHN(I,J)                                           COST3040
  141 CONTINUE                                                           COST3050
      J =  5                                                             COST3060
      SELD  =  SELD  +EHN(I,J)                                           COST3070
      J =  6                                                             COST3080
      SETR= SETR + EHN(I,J)                                              COST3090
      J =  7                                                             COST3100
      SEDS  =SEDS +  EHN(I,J)                                            COST3110
  380 CONTINUE                                                           COST3120
  C   COSTS FOR ENTIRE  SECTION                                          COST3130
  C   SXYZE = QUANTITY OF  XYZ USED ON ENTIRE SECTION IN 1 YEAR          COST3140
  C                                                                      COST3150
      SEDSE =  LOS * SEDS                                                COST3160
      SEDTE =  LOS * SEDT                                                COST3170
      SELDE =  LOS * SELD                                                COST3180
      SEMGE  = LOS * SEMG                                                COST3190
      SERLE =  LOS * SERL                                                COST3200
      SETRE =  LOS * SETR                                                COST3210
      SEWTE = LOS*SEWT                                                   COST3220
      SLCE = LOS*SLC                                                     COST3230
      SLEOE = LOS*SLEO                                                   COST3240
```

```
      SLFE = SLF*LOS                                                    COST3250
      SLGE = SLG*LOS                                                    COST3260
      SLTDE = LOS*SLTD                                                  COST3270
      SMBE = SMB* LOS                                                   COST3280
       SMBAE= SMBA * LOS                                                COST3290
      SMCAE = SMCA*LOS                                                  COST3300
      SMDE = SMD*LOS                                                    COST3310
      SMGE = SMG*LOS                                                    COST3320
       SMPE  = SMP*LOS                                                  COST3330
      SMWE = SMW*LOS                                                    COST3340
C     CAPITAL COSTS OF ROAD MAINTENANCE                                 COST3350
C     KXYZ =  CURRENCY COSTS OF XYZ FOR ENTIRE SECTION                  COST3360
C     UXYZ = UNIT PRICE OF XYZ                                          COST3370
C                                                                       COST3380
      KEDT = UEDT*SEDTE                                                 COST3390
      KEDS = UEDS*SEDSE                                                 COST3400
      KELD  = UELD*SELDE                                                COST3410
      KEMG= UEMG*SEMGE                                                  COST3420
      KERL  = UERL*SERLE                                                COST3430
      KETR  = UETR*SETRE                                                COST3440
      KEWT = UEWT*SEWTE                                                 COST3450
      KLC = ULC*SLCE                                                    COST3460
      KLEO = ULEO*SLEOE                                                 COST3470
      KLF = ULF*SLFE                                                    COST3480
      KLG = SLGE*ULC                                                    COST3490
      KLTD = ULTD*SLTDE                                                 COST3500
      KMB = UMB *SMBE                                                   COST3510
      KMBA = UMBA*SMBAE                                                 COST3520
      KMCA = UMCA*SMCAE                                                 COST3530
      KMD = UMD*SMDE                                                    COST3540
      KMG = UMG*SMGE                                                    COST3550
      KMP = UMP*SMPE                                                    COST3560
       KMW =  UMW*SMWE                                                  COST3570
C      COSTS OF LABOR,EQUIPMENT,AND MATERIALS                           COST3580
      KLABR= KLC+KLEO+KLF+ KLTD                                         COST3590
      KEQ=KEDT+KEDS+KELD+KEMG+KERL+KETR+KEWT                            COST3600
```

```
      KMAT=KMB+KMBA+KMCA+KMD+KMG+KMP+KMW
      KLEM=KLABR+KEQ+KMAT
CC    END OF COST SUM SECTION
      IF (ISWTH(1)) 711,711,712
712   CONTINUE
      WRITE(IPRNT,1011)
 1011 FORMAT(1H0,'THE FOLLOWING ARRAYS CONTAIN DETAILED ACCOUNTS OF THE
     1MAINTENANCE EFFORT'/' COLUMNS DEAL WITH EQUIPMENT TYPES, WHILE ROW
     2S REFER TO VARIOUS TASKS'//' TASKS ARE ',T100,'EQUIPMENT TYPES ARE
     3')
      WRITE(IPRNT,1012)
 1012 FORMAT(1X,'1 BLADING DURING DRY SEASON',T100,'MOTOR GRADER'/' 2 RE
     2GRAVELLING',T100,'WATER TRUCK'/' 3 VEGETATION CONTROL',T100,'ROLLE
     3R'/' 4 DRAINAGE-CULVERT AND DITCH CLEANING',T100,'DUMPTRUCK'/
     4' 5 BLADING DURING WET SEASON',T100,'LOADER'/' 6 PATCH WITH COLD M
     5IX',T100,'TRACTOR'/)
      WRITE(IPRNT,1013)
 1013 FORMAT(1X,' 7 HAUL COLD MIX',T100,'WATER TRUCK'/' 8 PLACE AND ROLL
     1 BITUMINOUS SEALCOAT'/' 9 HAUL AGGREGATE FOR SEAL COAT'/' 10 PLACE
     2 AND COMPACT PATCHING MIX IN RUTS'/' 11 HAUL RUT PATCHING MIX'/
     3' 12 SHOULDER MAINTENANCE '  )
      WRITE(IPRNT,10141  )
10141 FORMAT(1H0,' AN ARRAY ELEMENT INDICATES THE PHYSICAL QUANTITY EXPE
     1NDED PERFORMING A TASK'/'   WITH A CERTAIN TYPE OF MACHINERY')
      WRITE(IPRNT,1014)
 1014 FORMAT('0 EQUIPMENT HOURS  BY TASKS')
      WRITE( IPRNT,101)  ((  EHN(I,J) , J = 1,7),I = 1,12)
      WRITE(IPRNT,1015)
1015   FORMAT ('0 HOURS OF COMMON LABOR ' )
      WRITE( IPRNT,101)  ((  LC (I,J) , J = 1,7),I = 1,12)
      WRITE(IPRNT,1016)
1016  FORMAT('0 EQUIPMENT OPERATOR HOURS ')
      WRITE( IPRNT,101)  ((  LEO(I,J) , J = 1,7),I = 1,12)
      WRITE(IPRNT,1017)
1017  FORMAT('0 FOREMAN HOURS')
      WRITE( IPRNT,101)  ((  LF (I,J) , J = 1,7),I = 1,12)
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```
      WRITE(IPRNT,1018)                                                 COST3970
1018  FORMAT('0 GREASER HOURS')                                         COST3980
       WRITE(IPRNT,101) ((LG(I,J),J=1,7),I=1,12 )                       COST3990
      WRITE(IPRNT,1019)                                                 COST4000
1019  FORMAT('0 TRUCK DRIVER HOURS')                                    COST4010
      WRITE( IPRNT,101)  ((  LTD(I,J) , J = 1,7),I = 1,12)              COST4020
      WRITE(IPRNT,1020)                                                 COST4030
1020  FORMAT( '0 LITERS OF LIQUID ASPHALT'     )                        COST4040
      WRITE( IPRNT,101)  ((  MB (I,J) , J = 1,7),I = 1,12)              COST4050
      WRITE(IPRNT,1021)                                                 COST4060
1021  FORMAT('0 COLD MIX (TONS)')                                       COST4070
      WRITE( IPRNT,101)  ((  MBA(I,J) , J = 1,7),I = 1,12)              COST4080
      WRITE(IPRNT,1022)                                                 COST4090
1022  FORMAT('0 TONS OF AGGREGATE(PATCHING)')                           COST4100
      WRITE( IPRNT,101)  ((  MCA(I,J) , J = 1,7),I = 1,12)              COST4110
      WRITE(IPRNT,1023)                                                 COST4120
 1023 FORMAT('0 LITERS OF DIESEL FUEL')                                 COST4130
      WRITE( IPRNT,101)  ((  MD (I,J) , J = 1,7),I = 1,12)              COST4140
      WRITE(IPRNT,1024)                                                 COST4150
1024  FORMAT('0 TONS OF GRAVEL')                                        COST4160
      WRITE( IPRNT,101)  ((  MG (I,J) , J = 1,7),I = 1,12)              COST4170
      WRITE(IPRNT,10241)                                                COST4180
10241 FORMAT('0 LITERS OF GASOLINE ')                                   COST4190
      WRITE( IPRNT,101)  ((  MP (I,J) , J = 1,7),I = 1,12)              COST4200
      WRITE(IPRNT,1025)                                                 COST4210
1025  FORMAT('0 CUBIC METERS OF WATER')                                 COST4220
      WRITE( IPRNT,101)  ((  MW (I,J) , J = 1,7),I = 1,12)              COST4230
101   FORMAT( 1H0/ (7F10.1 ))                                           COST4240
711   CONTINUE                                                          COST4250
      MTCT(1) = KLABR                                                   COST4260
      MTCT(2)= KEQ                                                      COST4270
      MTCT(3)= KMAT                                                     COST4280
      MTCT(4)= KLEM                                                     COST4290
      MTCT(5)=   SEMG                                                   COST4300
      MTCT(6) = SEWT                                                    COST4310
      MTCT(7)= SERL                                                     COST4320
```

```
      MTCT(8)= SEDT                                                     COST4330
      MTCT(9)= SELD                                                     COST4340
      MTCT(10)= SETR                                                    COST4350
      MTCT(11)= SEDS                                                    COST4360
      MTCT(12)= SLC                                                     COST4370
      MTCT(13)= SLED                                                    COST4380
      MTCT(14)= SLF                                                     COST4390
      MTCT(15)= SLTD                                                    COST4400
      MTCT(16)= SMB                                                     COST4410
      MTCT(17)= SMBA                                                    COST4420
      MTCT(18)= SMCA                                                    COST4430
      MTCT(19)= SMD                                                     COST4440
      MTCT(20)= SMG                                                     COST4450
      MTCT(21)= SMP                                                     COST4460
      MTCT(22)= SMW                                                     COST4470
      MTCT(23)  = SLG                                                   COST4480
      RETURN                                                            COST4490
       END                                                              COST4500
```

```
      SUBROUTINE IMPRU
      REAL MAPOL,MUC,MTCT,LOS,WOS
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)
      DIMENSION APWC(4),AMTCT(4),PWC(4)
      DIMENSION ISWTH(5)
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAF
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD,
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH
C
C
C
C     IMPRU DETERMINES AVERAGE ROUGHNESS AND VERTICAL ACCELERATION AFTER MAINT.
C
      RUFF3=79.+2.96*PRERD-((PRECP/WOS)**0.5)
      IF (RUFF3-79.) 9301,9301,9302
 9301 RUFF3=RUFF
 9302 CONTINUE
      PRUFF=(RUFF1+RUFF2+RUFF3)/3.
C
      VA=-0.35+0.0057*PRUFF
C
      WRITE (IOUT,450) PRUFF,VA
  450 FORMAT (1H ,' AVERAGE ROUGHNESS FOR YEAR',2X,F10.2,///,' AVERAGE V
     1ERTICAL ACCELERATION FOR YEAR',2X,F10.2)
      RETURN
      END
```

```
      SUBROUTINE PWCAC                                                  PWCA0001
      REAL MAPOL,MUC,MTCT,LOS,WOS                                       PWCA0002
      DIMENSION CFAIL(20),EF(20),MAPOL(20),MUC(25),MTCT(25)             PWCA0003
      DIMENSION APWC(4),AMTCT(4),PWC(4)                                 PWCA0004
      DIMENSION ISWTH(5)                                                PWCA0005
      COMMON IIN,IOUT,IYEAR,NYEAR,NTYPE,DCBR,T,SCBR,CFAIL,EF,ENVFT,ITRAFPWCA0006
     1,ITCNT,SPTHW,TRINC,YTOTL,PRUFF,RUFF,VA,CP,RD,PRECP,WOS,LOS,PRERD, PWCA0007
     2MAPOL,MUC,MTCT,DISCR,SPVA,SMP,SMS,CMPR                            PWCA0008
      COMMON APWC,AMTCT,PWC,TOTAL,RUFF1,RUFF2,ISWTH                     PWCA0009
C                                                                       PWCA0010
C                                                                       PWCA0011
C                                                                       PWCA0012
C     PWCAC ESTIMATES:                                                  PWCA0013
C         1. DISCOUNTED LABOR, EQUIPMENT, MATERIAL AND SUM              PWCA0014
C            OF L,E, AND M COSTS                                        PWCA0015
C         2. ACTUAL COSTS OF 19 OTHER COST COMPONENTS                   PWCA0016
C                                                                       PWCA0017
C                                                                       PWCA0018
C     LOOP DISCOUNTS LABOR EQUIPMENT MATERIAL, AND TOTAL COSTS          PWCA0019
C                                                                       PWCA0020
      DO 820 I=1,4                                                      PWCA0021
      PWC(I)=MTCT(I)/((1+DISCR)**IYEAR)                                 PWCA0022
820   CONTINUE                                                          PWCA0023
C                                                                       PWCA0024
C                                                                       PWCA0025
      WRITE (IOUT,419)                                                  PWCA0026
419   FORMAT (1H0,' YEARLY COSTS',//)                                   PWCA0027
      WRITE (IOUT,420)                                                  PWCA0028
420   FORMAT (1H ,15X,' DISCOUNTED COSTS',10X,' ACTUAL COSTS')          PWCA0029
      WRITE (IOUT,421) PWC(1),MTCT(1)                                   PWCA0030
421   FORMAT (1H ,' LABOR COSTS',6X,F10.2,10X,F10.2)                    PWCA0031
      WRITE (IOUT,422) PWC(2),MTCT(2)                                   PWCA0032
422   FORMAT (1H ,' EQUIPMENT COSTS',2X,F10.2,10X,F10.2)                PWCA0033
      WRITE (IOUT,423) PWC(3),MTCT(3)                                   PWCA0034
423   FORMAT (1H ,' MATERIALS COST',3X,F10.2,10X,F10.2)                 PWCA0035
      WRITE (IOUT,424) PWC(4),MTCT(4)                                   PWCA0036
```

```
  424 FORMAT (1H ,' TOTAL COSTS',6X,F10.2,10X,F10.2)
C
      IF (ISWTH(2)) 901,901,902
  902 CONTINUE
      WRITE (IOUT,440) (MTCT(I),I=1,23)
  440 FORMAT (1H ,' MTCT   =',F10.2)
  901 CONTINUE
C
C     ACCUMULATE COSTS  PWC AND ACTUAL
C     LOOP TO ACCUMULATE
      DO 821 I=1,4
      APWC(I)=APWC(I)+PWC(I)
      AMTCT(I)=AMTCT(I)+MTCT(I)
  821 CONTINUE
C     WRITE ACCUMULATED COSTS TO DATE
      WRITE (IOUT,425)
  425 FORMAT (1H0,' ACCUMULATED COSTS',///,15X,' DISCOUNTED COSTS',10X,'
     1ACTUAL COSTS')
C
C
      WRITE (IOUT,426) APWC(1),AMTCT(1)
  426 FORMAT (1H ,' LABOR COSTS',6X,F10.2,10X,F10.2)
      WRITE (IOUT,427) APWC(2),AMTCT(2)
  427 FORMAT (1H ,' EQUIPMENT COSTS',2X,F10.2, 10X,F10.2)
      WRITE (IOUT,428) APWC(3),AMTCT(3)
  428 FORMAT (1H ,' MATERIALS COST',3X,F10.2,10X,F10.2)
      WRITE (IOUT,429) APWC(4),AMTCT(4)
  429 FORMAT (1H ,' TOTAL COSTS',6X,F10.2,10X,F10.2)
      RETURN
      END
```

APPENDIX IV

Typical Print Out Of Model

The print out which follows was derived from a test on pavement thickness equal to 64.01 cm. All other variables are unchanged from the "Base Run." Output switches are set to omit details of maintenance quantities and maintenance costs.

```
**************************************************************************************************************************************

                                                INPUT DATA, INCLUSIVE OF TRAFFIC INPUT

**************************************************************************************************************************************
MAINTENANCE POLICY

    -1.00               -1.00               -1.00               -1.00                1.00
    0.0                 0.0                 0.0                 0.0                 0.30
    0.30                2.00                0.0                 0.0                 0.0
    0.0                 0.0                 0.0                 0.0                 0.0

UNIT COSTS FOR MAINTENANCE

     4.00                3.00                3.00                3.57                4.10
    0.0                 0.0                 5.25                7.17                8.20
    6.68                0.04                6.60                3.45                0.04
    3.56                0.07                0.0                 0.0                 0.0
    0.0                 0.0                 0.0                 0.0                 0.0

NTYPE =          6        DCBR =       10.00       T =       71.12

WOS =      45.75              LOS =       3.05

SCBR                  SPTHW           TRINC           TOTAL              ITRAF              ITCNT
     7.00                0.20            0.10           0.0                0                  0

    DISCR              NYEAR            SPVA
     0.07                20             0.70

OUTPUT SWITCH STATUS          -1          -1           1           1           1
NTYPE  =       6
 ITYPE         P                PC                T              DCBR
    1       28636.63          10.57             28.00          10.00
    2       30909.09          11.63             28.00          10.00
    3       30909.09          11.63             28.00          10.00
    4       15909.09           9.16             28.00          10.00
    5       18181.82          10.15             28.00          10.00
    6       41818.18          12.68             28.00          10.00
CFAIL
  13954.29
   6354.64
   6354.64
 774264.19
 247691.44
   1760.35
 EQUIVALENCE FACTORS
       1.00
       1.67
       1.67
       0.02
       0.06
       7.64
 ENVFT =   1.18
 DCBR = 10.00       SCBR =   7.00
```

```
*****************************************************************************************************************************************

                                                    YEAR =      1

 NTYPE =      6

TYPE AIRCRAFT     NO. COVERAGES    EQUIV. COVER
     1                 100.00          100.00
     2                 100.00          167.02
     3                 100.00          167.02
     4                 100.00            1.80
     5                 100.00            5.63
     6                 100.00          783.79
 TOTAL EQUIVALENT COVERAGES FOR YEAR =    1225.27
 TOTAL UNIFORM COVERAGES, SAME OR REFEED,=     1270.19
 ACCUMULATED COVERAGES =          1270.19
 RCHNG =      14.38        RUFF =       93.38        PRUFF =      79.00
 C+P,BEFORE MAINTENANCE =      56.36        RD,BEFORE MAINTENANCE =       7.38
 CRACKING AND PATCHING, AFTER MAINTENANCE =       22.55        RUT DEPTH AFTER MAINTENANCE =       7.38
     DELCP       DELRD       SMP        SMS         CMPR         FIXRD       FTP         FTS
   2576.62       7.38     773.59     773.59        0.0          0.0         0.30       0.30

 YEARLY COSTS

                 DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          9186.43             9829.48
 EQUIPMENT COSTS      1622.05             1735.59
 MATERIALS COST       2119.71             2268.09
 TOTAL COSTS         12928.19            13833.16

 ACCUMULATED COSTS

                DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          9186.43             9829.48
 EQUIPMENT COSTS      1622.05             1735.59
 MATERIALS COST       2119.71             2268.09
 TOTAL COSTS         12928.19            13833.16
 AVERAGE ROUGHNESS FOR YEAR        89.49

 AVERAGE VERTICAL ACCELERATION FOR YEAR          0.16
```

```
*******************************************************************************************************************

                                                        YEAR =      2

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =    1397.20
 ACCUMULATED COVERAGES =            2667.39
 RCHNG =       15.82        RUFF =      105.31        PRUFF =      89.49
 C+P,BEFORE MAINTENANCE =      98.76        RD,BEFORE MAINTENANCE =       12.22
 CRACKING AND PATCHING, AFTER MAINTENANCE =       53.03        RUT DEPTH AFTER MAINTENANCE =      12.22
     DELCP       DELRD      SMP        SMS         CMPR         FIXRD       FTP          FTS
   5486.62       4.85   1045.99    1045.99        0.0          0.0        0.30        0.30

 YEARLY COSTS


                    DISCOUNTED COSTS                 ACTUAL COSTS
 LABOR COSTS           11608.63                 13290.70
 EQUIPMENT COSTS        2049.73                  2346.74
 MATERIALS COST         2678.62                  3066.74
 TOTAL COSTS           16336.98                 18704.18

 ACCUMULATED COSTS


                   DISCOUNTED COSTS                 ACTUAL COSTS
 LABOR COSTS           20795.06                 23120.19
 EQUIPMENT COSTS        3671.78                  4082.33
 MATERIALS COST         4798.32                  5334.83
 TOTAL COSTS           29265.16                 32537.34
 AVERAGE ROUGHNESS FOR YEAR        100.90

AVERAGE VERTICAL ACCELERATION FOR YEAR          0.23
```

```
*****************************************************************************************************************************************

                                                        YEAR =      3

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =   1536.92
 ACCUMULATED COVERAGES =            4204.31
 RCHNG =      17.40        RUFF =     118.30       PRUFF =     100.90
 C+P,BEFORE MAINTENANCE =     142.28       RD,BEFORE MAINTENANCE =      17.28
 CRACKING AND PATCHING, AFTER MAINTENANCE =      88.73       RUT DEPTH AFTER MAINTENANCE =      17.28
     DELCP       DELRD      SMP        SMS          CMPR        FIXRD      FTP        FTS
   4083.00       5.06   1224.90    1224.90         0.0         C.0        0.30       0.30

 YEARLY COSTS


                    DISCOUNTED COSTS             ACTUAL COSTS
 LABOR COSTS             12704.93              15564.06
 EQUIPMENT COSTS          2243.31               2748.14
 MATERIALS COST           2931.58               3591.31
 TOTAL COSTS             17879.82              21903.50

 ACCUMULATED COSTS


                   DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS             33500.00              38684.25
 EQUIPMENT COSTS          5915.09               6830.47
 MATERIALS COST           7729.91               8926.14
 TOTAL COSTS             47144.93              54440.84
 AVERAGE ROUGHNESS FOR YEAR          113.31


AVERAGE VERTICAL ACCELERATION FOR YEAR          0.30
```

```
**********************************************************************************************************************************

                                                  YEAR =      4

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =   1690.62
 ACCUMULATED COVERAGES =            5894.93
 RCHNG =       19.14       RUFF =     132.46       PRUFF =     113.31
 C+P,BEFORE MAINTENANCE =     187.04        RD,BEFORE MAINTENANCE =      22.65
 CRACKING AND PATCHING, AFTER MAINTENANCE =     128.05       RUT DEPTH AFTER MAINTENANCE =      22.65
     DELCP       DELRD      SMP        SMS          CMPR        FIXRD      FTP         FTS
   4497.90        5.37   1349.37    1349.37        0.0         C.0        0.30        0.30

 YEARLY COSTS


                  DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          13080.36            17145.63
 EQUIPMENT COSTS       2309.59             3027.40
 MATERIALS COST        3018.21             3956.24
 TOTAL COSTS          18408.15            24129.26

 ACCUMULATED COSTS


                 DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          46580.35           55829.87
 EQUIPMENT COSTS       8224.68            9857.86
 MATERIALS COST       10748.11           12882.38
 TOTAL COSTS          65553.13           78570.06
 AVERAGE ROUGHNESS FOR YEAR       126.83


AVERAGE VERTICAL ACCELERATION FOR YEAR          0.37
```

```
**********************************************************************************************************************

                                                   YEAR =      5

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =   1859.68
 ACCUMULATED COVERAGES =          7754.60
 RCHNG =      21.06       RUFF =      147.89       PRUFF =     126.83
 C+P.BEFORE MAINTENANCE =     233.22       RD,BEFORE MAINTENANCE =      28.40
 CRACKING AND PATCHING, AFTER MAINTENANCE =      170.12       RUT DEPTH AFTER MAINTENANCE =       28.40
     DELCP       DELRD      SMP        SMS         CMPR       FIXRD      FTP        FTS
   4811.18        5.75   1443.35   1443.35        0.0        0.0        0.30       0.30

 YEARLY COSTS


                  DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          13076.09           18339.82
 EQUIPMENT COSTS       2308.84            3238.26
 MATERIALS COST        3017.22            4231.80
 TOTAL COSTS          18402.14           25809.87

 ACCUMULATED COSTS


                 DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          59656.43           74169.69
 EQUIPMENT COSTS      10533.52           13096.12
 MATERIALS COST       13765.34           17114.18
 TOTAL COSTS          83955.25          104379.88
 AVERAGE ROUGHNESS FOR YEAR       141.58

AVERAGE VERTICAL ACCELERATION FOR YEAR         0.46
```

```
*****************************************************************************************************************************

                                                                      YEAR =      6

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =   2045.65
 ACCUMULATED COVERAGES =          9800.25
 RCHNG =      23.16       RUFF =      164.75       PRUFF =      141.58
 C+P,BEFORE MAINTENANCE =      280.97       RD,BEFORE MAINTENANCE =      34.60
 CRACKING AND PATCHING, AFTER MAINTENANCE =      214.46      RUT DEPTH AFTER MAINTENANCE =      34.60
     DELCP       DELRD       SMP         SMS          CMPR        FIXRD       FTP         FTS
   5071.27        6.20    1521.38    1521.38          0.0         C.0        0.30        0.30

 YEARLY COSTS


                   DISCOUNTED COSTS             ACTUAL COSTS
 LABOR COSTS          12981.30             19331.27
 EQUIPMENT COSTS       2274.45              3413.32
 MATERIALS COST        2972.29              4460.57
 TOTAL COSTS          18128.02             27205.14

 ACCUMULATED COSTS


                   DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          72537.69             93500.94
 EQUIPMENT COSTS      12807.96             16509.43
 MATERIALS COST       16737.61             21574.74
 TOTAL COSTS         102083.25            131585.00
 AVERAGE ROUGHNESS FOR YEAR       157.70


AVERAGE VERTICAL ACCELERATION FOR YEAR         0.55
```

```
**********************************************************************************************************************************

                                                 YEAR =      7

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =    2250.21
 ACCUMULATED COVERAGES =          12050.45
 RCHNG =       25.48        RUFF =      183.18        PRUFF =      157.70
 C+P,BEFORE MAINTENANCE =      330.46        RD,BEFORE MAINTENANCE =       41.30
 CRACKING AND PATCHING, AFTER MAINTENANCE =      260.86       RUT DEPTH AFTER MAINTENANCE =       41.30
     DELCP       DELRD      SMP        SMS         CMPR        FIXRD      FTP         FTS
   5307.16        6.70   1592.15    1592.15        0.0         C.0        0.30        0.30

 YEARLY COSTS


                   DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          12598.62             20230.52
 EQUIPMENT COSTS       2224.54              3572.1C
 MATERIALS COST        2907.05              4668.06
 TOTAL COSTS          17730.20             28470.68

 ACCUMULATED COSTS


                  DISCOUNTED COSTS            ACTUAL COSTS
 LABOR COSTS          85136.25            113731.44
 EQUIPMENT COSTS      15032.5C             20081.53
 MATERIALS COST       19644.66             26242.8C
 TOTAL COSTS         119813.44            160055.63
 AVERAGE ROUGHNESS FOR YEAR        175.33

AVERAGE VERTICAL ACCELERATION FOR YEAR          0.65
```

```
*************************************************************************************************************************************

                                                        YEAR =      8

TOTAL COVERAGES FOR YEAR BY PER CENT INCREASE =   2475.23
 ACCUMULATED COVERAGES =            14525.68
 RCHNG =       28.03        PUFF =      203.36       PRUFF =      175.33
 C+P,BEFORE MAINTENANCE =      381.86       RD,BEFORE MAINTENANCE =      48.58
 CRACKING AND PATCHING, AFTER MAINTENANCE =     309.26       RUT DEPTH AFTER MAINTENANCE =       48.58
     DELCP       DELRD      SMP        SMS         CMPR        FIXRD       FTP        FTS
   5535.96       7.28    1660.79    1660.79        0.0         0.0        0.30       0.30

 YEARLY COSTS


                DISCOUNTED COSTS             ACTUAL COSTS
 LABOR COSTS          12282.03             21102.67
 EQUIPMENT COSTS       2168.63              3726.09
 MATERIALS COST        2834.00              4869.30
 TOTAL COSTS          17284.66             29698.07

 ACCUMULATED COSTS


                DISCOUNTED COSTS           ACTUAL COSTS
 LABOR COSTS          97418.25            134834.06
 EQUIPMENT COSTS      17201.13             23807.62
 MATERIALS COST       22478.66             31112.11
 TOTAL COSTS         137098.06            189753.69
 AVERAGE ROUGHNESS FOR YEAR      194.63

AVERAGE VERTICAL ACCELERATION FOR YEAR         0.76
```

APPENDIX V

Assumptions Concerning Maintenance

Predominately the assumptions dealing with maintenance cost operations used in this thesis follow those outlined in Alexander's Appendix D, Assumptions and Definitions (22). The only substantial deviation from these assumptions (other than those noted in the text) for airfield pavements concerns rut repair.

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 airfield 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:
    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)

---

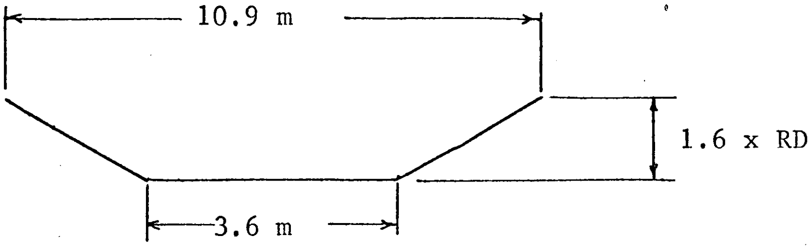
*Those assumptions which are not taken directly from Alexander (22) are preceded by an asterisk (*).

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 (FIXRD) will be approximately one-half of fraction of ruts filled (FRF).

$$FIXRD = 0.5\ (FRF)\ (RD)$$

*8. Assume that the shape and size of the average rut filled will be as follows (63,78):



Volume of patching material required for one kilometer of runway or taxiway:

$$CMPR = \frac{4 \times FRF \times 1.6\ RD \times 7.3m \times 1000m}{100\ cm/m}$$

$$= 467.2 \times FRF \times RD \qquad (A\text{-}V\text{-}1)$$