A PAVEMENT DESIGN AND MANAGEMENT SYSTEM FOR FOREST SERVICE ROADS—IMPLEMENTATION

FINAL REPORT—PHASE III

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RESEARCH REPORT 60

JANUARY 1979

U.S. FOREST SERVICE
WASHINGTON, D.C. 20250

COUNCIL FOR ADVANCED TRANSPORTATION STUDIES
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Final Report - Phase III

Research Report 60
January 1979

U. S. Forest Service Agreement No. 13-883

conducted for

Forest Service
U. S. Department of Agriculture

by the

Council for Advanced Transportation Studies

The University of Texas at Austin

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
Research Report 60		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code / 8. Performing Organization Report No.
A Pavement Design and Management System for Forest Service Roads - Implementation	5. January 1979 6. Research Report 60 8.
7. Author(s): B. Frank McCullough, David R. Luhr	
9. Performing Organization Name and Address: Division of Research in Transportation, Council for Advanced Transportation Studies, The University of Texas at Austin, Austin, Texas	10. Work Unit No. (TRAIS) 11. Contract or Grant No. FS-13-883
12. Sponsoring Agency Name and Address: FOREST SERVICE, USDA ENGINEERING STAFF P.O. Box 2417 WASHINGTON, DC 20013	13. Type of Report and Period Covered: Final 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report reviews the third phase of a three-phase project to develop and implement a pavement design and management system for low-cost, low-volume roads, in particular Forest Service roads. The specific objective of this phase was to implement a pavement management system called LVR (for low-volume roads) that was developed in Phase II. The implementation was carried out on a trial basis in selected Forest Service Regions.

Three training sessions instructed approximately 70 Forest Service engineers and planners from different parts of the country in the operation of program LVR. Following the training session was a one year period of program trial usage by the Forest Service. Changes were made in the program as users discovered inconsistencies or "bugs" in the new system.

The report includes results from a sensitivity analysis of the program, and an examination of the Rutting Prediction Model. Recommendations include revising the aggregate road failure models, and the establishment of a Forest Service system data base.

17. Key Words	18. Distribution Statement
Pavement Management System, Pavement Design System, Low-Volume Roads, Forest Service Roads, Sensitivity Analysis, Unsurfaced Roads, Logging Roads, Bituminous Surfaced Roads, Aggregate Surfaced Roads, Surface Treatment	No restriction on distribution. Available from National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

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PREFACE

This is the final report for Phase III of a three-phase study being conducted for the Forest Service by the Council for Advanced Transportation Studies, The University of Texas at Austin. The purpose of the total project is to develop and implement a pavement design and management system for low-volume roads, in particular Forest Service roads. The purpose of this report is to document the implementation of the pavement management system (LVR), on a trial basis in selected Forest Service Regions. Program developments that occurred during the implementation period, including a sensitivity analysis, are reported. Recommendations are made for future development of the Forest Service pavement management system.

The authors would like to acknowledge the work done by University of Texas project staff during this phase of the project; Rudolfo Tellez performed and analyzed the sensitivity analysis of LVR variables, Jose Diaz investigated the Rutting Prediction model, and David McKenzie prepared the LVR program documentation. The assistance of Dorothy Kenoyer and Susan Allen in the preparation of the manuscript is also acknowledged.

The authors appreciate the helpful suggestions made by the project's Forest Service advisory committee. As a result of their comments, the final product of this study will be particularly relevant to immediate Forest Service concerns. The committee includes representatives from various Regional Offices and the Washington, D.C., Office and consists of the following individuals: Adrian Pelzner (Project Coordinator), Ron Williamson, Martin Everitt, Doug Scholen, Bob Hinshaw, Duane Logan, Ted Stuart, Eugene Hansen, and Skip Coughlan.

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GLOSSARY OF TERMS*

ADT	Annual Average Daily Traffic
BDFT & BDFTIN	Input variables for LVR used to designate aggregate loss as a function of timber haulage
BONE	Input variable for LVR used to show the rate of non-traffic deterioration (B1)
ESAL	Equivalent Single-Axle Load, used to combine different combinations of axle loads into one single equivalent (usually 18-kips)
LVR	(Low-Volume Roads) computerized pavement design and management system
NM	Input variable for LVR which defines the number of materials available, excluding the subgrade
NLAY	Input variable for LVR used to designate the number of layers previously constructed
OVMAXL	Input variable for LVR which defines the maximum thickness of an individual rehabilitation
OVMIN	Input variable for LVR which defines the minimum thickness of an individual rehabilitation
P2	Pavement Serviceability Index (PSI) at which rehabilitation must be performed
P2P	Pavement Serviceability Index (PSI) which would result from non-traffic deterioration in infinite time
RUTT	Computer routine in LVR, used in the Rutting Prediction Model
USERAG	Computer routine in LVR, used in the Aggregate Loss Model
XTTO	Input variable for LVR which defines the minimum length of a performance period

*NOTE: Terms which are used in the documentation are included in an additional glossary in Appendix F.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Road building and transportation administration are an important and integral part of the resource management process in the United States Forest Service. To carry out its management responsibilities for Federal forest and watershed lands, the Forest Service is building and maintaining one of the largest and most complex transportation systems in the world. The Forest Service presently manages over 220,000 miles of roads throughout the United States, which represents an approximate investment of $3.5 billion. To help meet the demand for access to forest land, projected plans include the construction of 116,000 miles of new roads and the reconstruction of many existing roads.

The pavement for such an extensive road system represents a sizeable investment. For the 10,000 miles of roads to be constructed or reconstructed in 1979, the pavement cost will be approximately $75 million. In the early 1970's the Forest Service decided that a system must be developed to efficiently manage this investment. Because of the complexitites involved in efficiently designing, maintaining and managing pavements in such an extensive system, the University of Texas and the U. S. Forest Service initiated a cooperative study in 1972 to develop a pavement management system that would be applicable to Forest Service roads. The work was planned to proceed in three phases:

I - Conduct a feasibility study to ascertain the practicality of developing such a system for the Forest Service.

II - If Phase I was positive, develop a working pavement management system.

III - Implement the working system on a trial basis in selected Forest Service design offices.

The Phase I report, "A Pavement Design and Management System for Forest Service Roads - A Conceptual Study," (Ref 1) presented a conceptual pavement management system for low-volume roads (LVR), in particular Forest Service roads. After acquiring background information and investigating the present state-of-the-art of Forest Service and other low-volume pavement design concepts, an assessment of the Forest Service needs for a pavement management system was made. It found that emphasis was placed on (1) optimizing the total pavement investment, (2) providing pavement performance prediction methods for planning purposes, (3) optimizing resource management efforts, (4) providing a tool for evaluating the effectiveness of specific pavement designs, and (5) unifying design efforts within the Forest Service. As a result of the Phase I report, it was concluded that such a pavement management system was feasible and should be pursued in the next phase.

The Phase II report, "A Pavement Design and Management System for Forest Service Roads - A Working Model," (Ref 2) presented the principles of the working system and the development of several key mathematical models used in the system. The report explained the failure criteria used in the performance model and described other models related to traffic, structural design, maintenance, user delay, and vehicle operating cost. Separate programs were developed for aggregate surfaced and bituminous surfaced roads.

The objective of this current report is to document the experience gained in the trial use of the LVR program as a working pavement management system.

PHASE III - IMPLEMENTATION OF LVR

Objective

The specific objective of this third phase of the project was to implement the working LVR pavement management program, on a trial basis, in selected regions of the Forest Service. During implementation, model modifications were to be made and documented to assist in making LVR operational in standard Forest Service procedures. As stated in the Phase II Final Report, it was proposed that the objective could be realized by performing the following tasks:

(1) Conduct a sensitivity analysis of program variables.
(2) Conduct a trial usage of LVR.
(3) Conduct training sessions for Forest Service personnel.
(4) Plan program revisions and future improvements.
(5) Prepare user's manual.
(6) Estimate related vehicle operating costs.
(7) Extend the Forest Service trial usage.
(8) Investigate interaction with Forest Service Road Design System (RDS).

Procedure

The work plan (see Appendix B) to accomplish these tasks was divided into three parts, (a) trial usage and training sessions, (b) program revisions, documentation, and extension of the trial usage, and (c) other research and development.

The LVR trial usage began in the early stages of Phase III, in order to solve practical problems that would develop as engineers in the field began to use the new program. To allow sufficient time for Forest Service personnel to assess the program, training sessions to acquaint the new users with LVR commenced during the first quarterly period of the third phase of the project.

During this trial usage period, the work plan called for continuous analysis and modification of the model by the project staff. Any irrationalities or programming errors were analyzed, evaluated and corrected. The LVR program was documented at different levels of sophistication, ranging from a conceptual flowchart and brief explanations of subroutines to a detailed flowchart with a listing of the code for a computer programmer. As new developments occurred, the program documentation and User's Manual were updated to reflect the changes. Following the initial trial stage, other users from different regions were included in the implementation in order to extend the trial usage and gain a wider base of experience.

As the trial usage continued, other research and development work was done by the project staff. This primarily involved a sensitivity analysis, which evaluated the effect of change of the magnitude of a variable on total project cost and rehabilitation strategy, and also indicated problem variables or "bugs" in the program. Information from the sensitivity analysis concerning the behavior of certain variables under different conditions was incorporated in the documentation of the LVR program. Other work was carried out in related areas of vehicle operating cost, aggregate loss, and other items pertaining to specific user questions or comments. Technical memoranda that related to the supporting research and development were periodically written and distributed (Appendix E). During the entire usage period a "debugging" operation was carried out to correct problems and deficiencies within the program as identified by the user.

Phase III Report

To document the implementation of LVR, Chapter 2 describes the procedure and results of the Forest Service trial usage of the program. Chapter 3 includes the results of the sensitivity analysis, and describes other developments that were under way at the University of Texas during the implementation period. Chapters 4 and 5 analyze how the program can be used in its present form and what developments should be made in the future. A short summary of Phase III is provided in Chapter 6, and several appendices are included for supplemental information to this report.

CHAPTER 2. IMPLEMENTATION PROCEDURE AND RESULTS

INTRODUCTION

The procedure for implementing LVR into Forest Service operations is visually described by the flowchart in Fig 2.1. The basic philosophy in this procedure was (a) begin the trial usage at an early stage for "hands on" experience, (b) utilize feedback from the Forest Service users as a guide for program revisions, and (c) conduct model analyses at the same time in order to achieve maximum benefit from the trial usage.

To initiate the implementation, the first training session was held with Region 6 users in Portland on December 20 and 21, 1976. Initial trial usage of LVR (originally in Regions 6 and 8) allowed for program examination to determine if everything was working properly. Interaction between Forest Service and University of Texas project staff was very important in working out "bugs" and answering various questions on procedure. This interaction was a focal point of information regarding needed revisions in the model.

After implementation and trial usage was underway, the project staff began a more detailed analysis of the model. Information from the trial usage was helpful in selecting areas of needed study, and it soon became apparent that the Rutting and Aggregate Loss Models would have to be studied in more detail. The sensitivity analysis played a major role in examining the LVR input variables. Results indicated which variables the program was most sensitive to, helping to make necessary program revisions and analyze the total system.

Using the sequence of trial usage, user information, program evaluation, and model analysis, the implementation continued. With model revisions, the appropriate changes were made in the User's Manual and program documentation. This information, along with a detailed survey of LVR users, was then summarized for this final report.

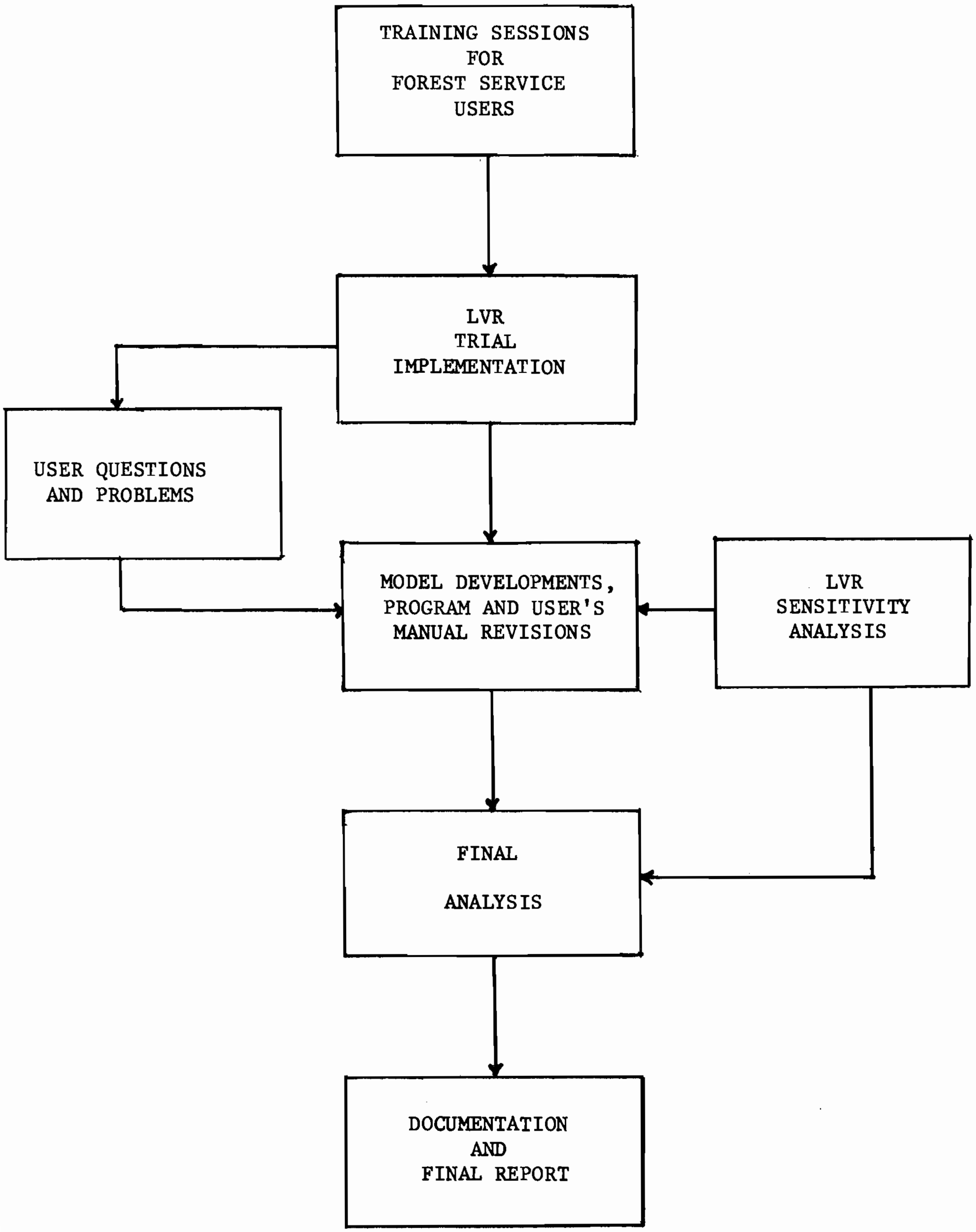

Fig 2.1. Implementation flow chart.

LVR TRAINING SESSIONS

A total of four training sessions were presented by the project staff to introduce LVR to new Forest Service users. Two of these sessions were held in Portland, Oregon (Region 6), one in Atlanta, Georgia (Region 8), and one in Missoula, Montana (Regions 1, 2, 3, 4 and 9). A total of 70 Forest Service "students" attended the sessions. A list of the dates and attendees of the training sessions and a typical agenda are presented in Appendix C.

Usually, the first day of the session included project background, a discussion of the systems approach, discussions of the models included in the program and a detailed discussion of the LVR User's Manual. The second day usually included discussion and coding of an example problem, which was prepared and executed by the participants. Additional time was scheduled for selected individual problems of interest.

At some of the sessions, a problem with computer-terminal communications between the training location and the Fort Collins Computer Center caused difficulties in setting up input files. As a result of this problem, many of the participants indicated a desire for more "hands on" time with the computer in order to make runs using data brought from their respective Forests. A survey was conducted to get feedback on the adequacy of teaching aids, handout materials, and presentation techniques. The results of this evaluation indicated that the methods, materials, and techniques used were very well received.

In general, the project staff felt that the training sessions went very well. The participants were very cooperative and eager to learn about and to use the new program. The participants, in post-training session evaluations, were asked if the training sessions had been satisfactory. All responded that they were pleased with the sessions, with a few suggesting future sessions be offered to refresh experienced users and introduce new ones.

LVR MODEL MODIFICATIONS

One of the important characteristics of the implementation procedure was the feedback of Forest Service user experience with LVR. This information often called attention to modifications that were necessary to correct or improve the model. Listed below is a summary of some of the model changes which are discussed further in Summary of Technical Memorandums (Appendix E).

Deflection Design Procedure

At the request of Region 6, a deflection design procedure being used in that Region was incorporated into LVR. This model calculates initial design thicknesses for asphalt surfaced pavements and asphalt overlays given deflection measurements taken in the field with a Dynaflect or Benkelman Beam. These deflection designs are based on calculations and procedures used in the publication "Development of the Asphalt Institute's Deflection Method for Designing Asphalt Concrete Overlays for Asphalt Pavements" (Ref 3). The deflection model which was incorporated into LVR is documented further in Appendix E of this report. Further development of the deflection design method in LVR will be forthcoming in later versions of the program.

Structural Model for Aggregate Roads

As a result of a request from Mr. John Bragg of the Ouachita National Forest, a change was made in the AASHTO structural model as it applies to aggregate surfaced roads. The change involved the layer checking scheme that insures the surface layer is adequately thick to support the loads appropriate for the soil support value of the underlying granular layer or the subgrade. Since the surface layer for an aggregate road does not perform the same function, structurally, as the surface layer of an asphalt road, this check was deemed inappropriate and is now bypassed when aggregate surfaced roads are being designed. A discussion of this change is included in Appendix E.

Non-Traffic Deterioration Parameters

During the early sensitivity analysis, certain effects caused by non-traffic deterioration parameters were noted and documented in a Technical Memorandum (Appendix E). It was determined that when the program indicates that there are no feasible designs for a given set of input data, it may be because the swelling clay parameters P2P (minimum level of PSI due to non-traffic deterioration) and BONE (rate of deterioration) force the serviceability index to drop to the unacceptable level of P2 too quickly. If P2P is less than P2, it may be impossible to remedy this by relaxing any of the constraints related to cost, traffic, or construction. To inform the user of this situation when it occurs, the following message was implemented in the program: "Non-traffic deterioration parameters are too restrictive for all possible designs. Decrease XTTO or reconsider values for P2, P2P, and BONE."

Changes in Program Code

Appendix E also pertains to corrections made in the LVR program code. These minor modifications are usually the result of queries or "bugs" found in the execution of the program. Among the items modified were the cumulative traffic model, the cumulative aggregate loss function, and the rehabilitation strategy for aggregate surfaced roads. As these problems were identified, the program code was checked to determine if the models were executing correctly. Corrections were made and the program was rerun to verify that it was operating properly.

DOCUMENTATION

User's Manual

Throughout the implementation phase of this project, the User's Manual was continuously updated as changes occurred in the program or suggestions were made to improve the instructions. As a result, the present guide is different from the one issued with the Phase II Final Report. The final version of the User's Manual is included as a separate appendix to this report.

Program Documentation

To aid in understanding the LVR program, and to make future changes to the program easier, a documentation of LVR is included as Appendix F to this report. It includes a brief description of each of the 21 subroutines in LVR, and flowcharts are provided for those routines having principal roles in the optimization process. This level of documentation is primarily intended for the engineer who wants to know basically where and how the different models are implemented in the program, but does not want to go through the algorithms in great detail.

Appendix F also contains a dictionary of program names (or variables) and a table of names cross-referenced with the subroutines in which they are used. The latter item should help the programmer to alter a portion of the program without causing unfortunate results elsewhere in the program.

Not included in this report is a detailed computer-generated flowchart with a complete cross-referenced listing of the FORTRAN code. This will accompany the program being delivered to the Forest Service computer center. The different levels of documentation presented should provide adequate coverage of the program for each of the anticipated types of users.

TRIAL IMPLEMENTATION

The trial implementation of the LVR program was designed to give Forest Service engineers and planners an opportunity to use and evaluate the model over a period of time. It also served as a test for the program, allowing observation of how it would perform under different Forest Service applications in various parts of the country. It was hoped that these applications would reveal any problems with the LVR program and documentation that had not yet been discovered.

The implementation began with Regions 6 and 8, and training sessions were held in December 1976 for Region 6 and March 1977 for Region 8 to introduce the prospective users to the LVR program. These two regions were chosen because they represented a general range of Forest Service transportation facilities across the nation. Region 6 included mostly log hauling roads, on which heavy loadings could be expected, and many new roads were anticipated. Region 8, on the other hand, had a relatively low volume of log hauling traffic and concentrated more on roads for recreational purposes. Because of the dependence of Forest Service road financing on merchantible timber, Region 6 also tended to have more money available for roadway construction and maintenance than Region 8. For these reasons, it was felt the two Regions would give a good cross section of constraints, applications, and experiences for the LVR program.

On the basis of the successful beginning of the implementation period and increased interest from other Regions, Mr. Adrian Pelzner, Project Coordinator, suggested that the implementation be expanded to include certain other Regions. This would benefit the study by increasing the exposure of the trial implementation and at the same time benefit the Forest Service by introducing more users to the new system. As a result of this suggestion, the project staff conducted a training session in October 1977 which included members from Regions 1, 2, 3, 4, and 9. Subsequent interactions with these Regions indicated that the program was being implemented in a number of their Forests.

During the implementation period the project staff served as consultants to users who had questions or problems with the program. This interaction served two purposes. First, it assisted the user in his understanding and operation of the program and supplied an additional assurance of a direct and immediate source of assistance. Secondly, it was a valuable feedback source for the University project staff in analyzing and making changes to the model. Listed below are typical examples of the interaction that took place between Forest Service users and University of Texas project staff.

SUMMARY OF FOREST SERVICE-UNIVERSITY PROJECT STAFF INTERACTION: OCTOBER 1977 - JUNE 1978

October

As a follow-up to the training session at Missoula, Montana, a number of communications between Forest Service and University of Texas personnel took place regarding the performance of LVR with actual design problems. It had been discovered in March (by Ken Buss, Region 6) that the program would not consider a single layer design. A code revision eliminated this problem and users were informed of this in early October (Appendix E). Another problem revealed by Forest Service personnel was the failure of the rutting prediction algorithm to execute properly for certain kinds of input. Roy Arnoldt (Region 6) and Rich Kennedy (Region 1) had each encountered time-limit aborts as a result of this error in coding (Appendix E). Other difficulties were due to items in the program input guide that needed clarification. Gary Schulze (Region 9) was unable to run a problem because of the 40-design limit for printed output. Martin C. Everitt (Region 2) offered some detailed comments and pointed out ambiguities in the User's Manual. As a result of these interactions, several code revisions were made in the program. These revisions were relayed to Mack Litton who maintained the program at the U.S.D.A. computer center in Fort Collins, Colorado.

November

While attempting to run an aggregate design problem prepared by Forest Service personnel at the Missoula training session, it was discovered that the subroutine USAG, which simulates aggregate loss, did not function properly with respect to the non-linear traffic model. Hence, the subroutine was rewritten and sent to Fort Collins on 15 November. Additional code changes dealt with the initialization of certain input variables and were necessary to prevent possible execution aborts (Appendix E). On 30 November, Martin C. Everitt was contacted regarding a "no feasible designs" result for one of his problems. It was learned that the non-traffic deterioration parameters may be so restrictive that no design, regardless of configuration, would be considered by the program. As a result of this communication, and of similar previous experiences, it was concluded that the program should provide a warning message to this effect: "Non-traffic deterioration parameters are too restrictive for all possible designs. Decrease XTTO or reconsider values for P2, P2P, and BONE."

December-January

In early December, Robert Hinshaw (Region 1) contacted the University of Texas about his inability to obtain from LVR a one-layer aggregate design that included a rehabilitation strategy for the analysis period. He would either get no feasible designs or would have to increase the thickness to ten inches to get a design lasting the entire analysis period. On 12 December, Gene Hansen (Region 4) encountered the same difficulty with a two-layer aggregate design. An inspection of the portion of the program which generates candidate designs revealed that the three deterioration models for aggregate roads (Rutting, Aggregate Loss, and AASHTO) did not interact appropriately. It was not necessary to revise the models, but some of the code determining the program's logic had to be changed (Appendix E). This change, along with some minor revisions pertaining to variable values, was relayed to Fort Collins on 17 January. Specific design problems referred to above were successfully run on the University of Texas computer and sent to the respective users.

February-March

On 7 February, Mr. Ron Williamson was informed of the changes made to the program with respect to the aggregate road deterioration models. Mack Litton provided our staff with a Fort Collins LVR computer output so that the correct implementation of the new changes could be verified. A comparison showed that the results from the Forest Service computer were essentially identical to those obtained at the University of Texas. On 27 February, Robert Hinshaw (Region 1) ran an aggregate design problem in which the model developed by John Lund (Ref 13) was used for predicting aggregate loss. The computer results did not seem to agree with his hand calculations. An examination of the same data at the University of Texas revealed that the program was functioning correctly, but that the Lund model was inadequate for cases involving significant non-truck traffic. This prompted a reevaluation of the model in which it was concluded, after consultation with John Lund, that a loss prediction equation based on truck traffic alone would be more appropriate. Forest Service users were advised that the direct input option, which allows the user to specify the rate of aggregate loss, should be used until the new model is implemented (See Chapter 3).

April-May

During the sensitivity analysis, in which LVR was run many times, it was learned that the range of overlay thickness (OVMAXL minus OVMIN) was the variable most likely to cause long execution times. On 12 April, Robert Hinshaw encountered a time-limit abort when running a three-layer design requiring four aggregate additions during the analysis period. In this case, OVMAXL - OVMIN = 7 inches, and the same problem required 200 seconds on the University computer. It was reported that another Forest Service user had a similar experience. Further experimentation at the University of Texas suggested that the problem might be circumvented by keeping the range of thicknesses (both for initial construction and for overlay) as small as possible and running the program more than once, if necessary, to determine an optimum configuration. During this period, Mr. Hinshaw and Mr. Hansen made suggestions regarding appropriate input parameter ranges to be used in the aggregate road portion of the sensitivity analysis and recommended that certain items in the User's Guide be clarified, such as the variables BDFT and BDFTIN, which determine aggregate loss. It was also pointed out that the length of printed output was a limitation when an interactive terminal was used and that the inability to obtain a printed result rapidly could be a problem for users of the program.

The following table summarizes some of the difficulties experienced by users of LVR during this eight month period and the resulting changes to either the User's Guide or the program code.

	Problem	Action Taken
1.	No single layer designs	Code change involving parameters NLAY and NM
2.	Error in performance equation of Phase II report, p. 13	Errata sheet distributed to FS users
3.	Time limit aborts with some aggregate designs	Code correction in routine RUTT

4.	Program fails to execute when more than 40 designs are requested	Program default set to 40
5.	Long execution times or execution failure when aggregate loss is input directly	Subroutine USERAG rewritten
6.	Program aborts due to arithmetic errors	Code changes made for initial variable values
7.	Inability to get feasible designs by increasing layer thickness	Message provided to warn of restrictive non-traffic deterioration parameters
8.	Inability to get aggregate designs with rehabilitations	Code revision to allow proper interaction of performance and rutting models
9.	Failure of the Lund aggregate loss equation for some distributions of traffic	Loss prediction equation is replaced and User's Guide is changed to reflect new parameters
10.	Long execution times for multi-layered aggregate designs	User's Gude revised to emphasize the effect of OVMAXL-OVMIN
11.	Difficulties with input parameters NM, NLAY, BDFT, BDFTIN, DA	Program defaults are provided in the code and User's Guide is clarified

RESULTS OF IMPLEMENTATION

During the trial implementation of LVR, over 70 Forest Service personnel from 30 Forests and seven Regions were introduced to the program. This represented a cross section of the planners, engineers, and managers currently working in many different areas of the country. It was believed that with this amount of exposure, LVR would be tested against most, if not all, possible applications of Forest Service usage.

To ascertain the type of usage that LVR had received and any additional needs for model revision and development, the project staff conducted a questionnaire survey of some of the users in all Regions where LVR was introduced. Depending on the Region, this generally was after one year of trial implementation. A copy of the questionnaire used and an abstract of the survey results are included in Appendix D of this report. The following is a general summary of the comments from the questionnaire.

Usage of LVR

The general response from Forest Service personnel around the country was the belief that LVR was a good program and more frequent use was expected in the future. However, up to this time, it has received little use. This was for a variety of reasons; some users had problems with data processing; some did not have the time or resources to experiment with the program; others did not as yet have authorization to use LVR; and some others had been transferred to other duties since the training session and no longer designed pavements. Three or four users simply did not like the program, but they were a small minority. Most gave the overall program high marks and said they planned to use it more in the future.

The Internal Models

The reply from most users concerning asphalt surface design was very favorable. Most had satisfactory results with few problems in executing the program. For aggregate surfaced roads, however, many users had unsatisfactory experiences. Problems ranged from unreasonable designs to excess computer execution time. Many questioned the accuracy of the aggregate loss and rut depth models. This has also been an area of concern to The University of Texas Project Staff and is discussed further in Chapter 3.

One common item that was mentioned by many users was the intention to use deflection design methods more in the future. With an increase in the number of new asphalt surfaced roads built, and an interest in determining overlay strategies for existing asphalt roads, it was suggested that the deflection model be expanded and improved.

Suggestions from Forest Service personnel concerning changes and additional capabilities of the models were very useful. Ranging from an input for dust abatement cost to interaction with RDS, these remarks are being considered for present and future development. Many of these comments and suggestions are listed in Appendix D.

Regional Office Opinion

The questionnaire survey also included Forest Service management at every Regional Office that participated in the trial implementation. In general, the response was favorable towards the program, and like the users at the Forest level, Forest Service Regional Office personnel planned to make more use of LVR in the future.

One repeated concern was having adequate personnel and the time and training to implement a new method such as LVR. Another question involved the Regional Offices' ability to maintain in-house staff capable of training new users and handling user problems.

One very important comment involved the maintenance of the program itself. It was stated that considerable attention will be required to keep the models up to date, and, if this is not done on a continuing basis, the program may become obsolete in three to five years. This comment is also applicable to any design method.

Overall, the Regional Office personnel showed a strong interest in continuing the use of LVR in the future. They were very aware of the importance of up-to-date information and model maintenance in the future performance of the program.

Expanding the Implementation

As a result of this trial implementation of LVR, the Forest Service now has the program operational in selected areas across the country. Because of the less than adequate usage of the program in this short time of implementation, it is recommended that the Forest Service expand its implementation of the pavement management system (LVR). With more participation, an increased data base could be used to generate more meaningful and beneficial results. Throughout the questionnaire survey the users remarked about the need for additional information. This was particularly true in two areas: aggregate road design and vehicle operating cost. Some stressed the importance of a standard road rating system. Others remarked about the unknown relationship between gravel loss, blading frequency, environment, material type, and traffic. Another user desired information on vehicle operating costs, particularly when comparing aggregate and asphalt surfaced roads. With LVR now operational for the Forest Service, it could be a good tool for gathering and analyzing new information during an expanded implementation period.

CHAPTER 3. DEVELOPMENTS DURING IMPLEMENTATION

INTRODUCTION

Because the adequacy of the LVR program is dependent on the integrity of the individual models, further refinement of the models continued through the implementation phase. These developments were part of a continuing effort to investigate and evaluate the various components of the program in order to improve the analysis of results and make future changes and needs more apparent.

The major effort in this process was the completion of the sensitivity analysis of the LVR program. This analysis, along with input from Forest Service users, led to discovery of deficiencies in the current versions of the Rutting and Aggregate Loss Models. As a result of these discoveries, a detailed study of the Rutting Model was performed in order to determine whether improvements could be made. The Aggregate Loss Model was also investigated to determine whether more developments were necessary to make the model satisfactory for Forest Service use. Other areas of interaction with the LVR program, such as the University of California model for computing vehicle operating costs, were investigated for possible improvements to the program.

PROGRAM COMPATIBILITY

During the implementation phase, the project staff was notified that the Forest Service will be changing to a different type of computer processing system. There was some concern that the present program, which is currently used on a UNIVAC system, would not be compatible with IBM type processing. To reduce the possible difficulties with this situation, all of the important models and most of the others have been altered to make them both CDC and

IBM compatible. Any additional changes will be able to be easily performed by Forest Service programming staff.

VEHICLE OPERATING COSTS

Vehicle operating cost is considered to be an important parameter when analyzing alternative strategies in roadway design. When comparing aggregate and asphalt pavements, it is necessary to consider the additional vehicle operating costs inherent in an aggregate road, even though the construction costs are much less than those for an asphalt surface. This parameter has even more importance in Forest Service applications because of the commercial aspect of many forest road users. Forest industry users will be able to save money on hauling and vehicle maintenance costs when using a high quality forest road. With these reduced costs, industry can afford to pay more for timber purchases, which generates more revenue for the U. S. Treasury. Because of this unique relationship between the Forest Service and its road users, the consideration of vehicle operating costs is an important one.

LVR currently allows for input of vehicle operating costs, as described by the user in dollars per mile. The program will also calculate vehicle delay costs based on periods of pavement maintenance but has no capability to calculate operating costs based on terrain or type of road. The Institute of Transportation and Traffic Engineering at the University of California at Berkeley developed a program for the Forest Service entitled "U. S. Forest Service Vehicle Operating Cost Model" (Ref 4). This model calculates operating costs primarily by simulating tire wear and fuel costs, which are functions of speed, grade, and surface of the roadway. The program handles several classes of vehicle type, ranging from a passenger car to a loaded logging truck.

At the present time, we understand that the University of California program is operational on the Forest Service computer system. The program has been studied by the project staff at the University of Texas, and a small factorial of computer runs were made using a range of program variables in order to generate regression equations from the results. The analysis to date indicates that the regressions may be quite accurate, and in the future these equations may be incorporated into LVR to allow the program to compute vehicle operating costs for the user.

The sensitivity analysis performed on LVR showed that vehicle operating costs had no effect, and vehicle delay parameters had little effect, on cost differences between alternate pavement strategies. This, however, is primarily due to the fact that LVR does not incorporate the additional economic factors of cost-benefit trade-offs that were mentioned above. This analysis is important, and it appears the University of California model is a viable tool to assist in this analysis. It also appears that results from the University of California model may be incorporated into LVR in the future in the form of regression equations, to allow the program to calculate operating costs for the user.

LVR SENSITIVITY ANALYSIS

The basic concept for the sensitivity analysis, as part of the implementation process, is to evaluate the effect of changing the magnitude of a variable on the total project cost and rehabilitation strategy. In this way, the significant effects of different input variables can be compared. Based on these results, variables having a small effect can be fixed at a mean value and more effort spent on characterizing the most significant or sensitive variables. When this kind of information is used, there can be a substantial savings in resources required to characterize variables for pavement design.

Description of the Sensitivity Analysis

For a sensitivity analysis, one variable at a time is selected for study. The program is then run with the variable first at its low value and then at its high value, with all the other variables fixed at the average value. The process is then repeated for each input variable in the program.

This condition is called the "average level" since all the variables except the one being studied are held at an average value. This analysis was performed for both asphalt concrete paved roads and aggregate surfaced roads. Also, "low level" and "high level" conditions (which indicate that all variables are fixed at low values or high values respectively, except the variable being studied) were analyzed for paved roads in order to obtain additional information.

The analysis involved as many as 49 input variables for a three-layer design of paved roads and 47 variables for a two-layer design of aggregate roads. For this study, 340 computer runs of LVR were required, broken down as follows: 99 for paved roads average level, 99 for paved roads low level, 47 for paved roads high level, and 95 for aggregate surfaced roads at the average level.

The computer time required for program execution was also analyzed with respect to the different variables. This analysis showed that several variables, in addition to the failure criteria model for aggregate surfaced roads, caused excess computer time problems.

List of Variables, Values, and Ranges

A realistic range and an average value for each of the variables were obtained from Forest Service engineers at staff meetings, at training sessions, and in telephone conversations. Other values were discussed with University of Texas project staff, based on professional experience and information from the Texas State Department of Highways and Public Transportation. Data from technical references were also used. Low values were those associated with low costs (low traffic, high quality subgrade, etc.), and high values referred to those associated with higher costs (high traffic, poor subgrade, etc.).

Variable name, average value and range for each input variable are shown for paved roads and aggregate roads in Table 3.1.

Results of Analysis

The results from the sensitivity analysis are reported separately for asphalt concrete paved roads and aggregate surfaced roads. The variables are rated as having a significant effect, small effect, or no effect at all.

TABLE 3.1. LIST OF VARIABLES AND RANGES FOR USE IN THE SENSITIVITY ANALYSIS

Variable Name	** Low	Average	*** High
Miscellaneous Inputs			
Total number of materials available without subgrade	3	3	3
*Total number of materials available without subgrade	2	2	2
Width of each lane (feet)	12	12	12
*Width of each lane (feet)	14	14	14
Number of lanes	2	2	2
Interest rate (%)	6	8	12
Performance Variables			
Regional factor	0.5	1.0	3.0
Initial serviceability index (PSI)	4.5	4.2	3.8
Serviceability index after an overlay (P1)	4.5	4.2	3.8
Terminal serviceability Index (P2)	1.5	2.0	2.5
Non-traffic deterioration parameter (P2P)	3.0	1.5	0
Swelling clay parameter (b_1)	0	0.06	0.12
*Surface material less than 3/4 in. (%)	70	85	95

* For Aggregate Surfaced Roads Only
** Low - Value of variable that gives least cost
*** High- Value of variable that gives highest cost

(Continued)

TABLE 3.1. LIST OF VARIABLES AND RANGES (CONTINUED)

Variable Name	** Low	Average	*** High
Time Dependent Variables	Performance Period	Performance Period	Performance Period
Traffic			
--Daily traffic volume (other than logging trucks)	First - - 50 Second - - 50 10	First - - 100 Second - - 100 25	First - - 300 Second - - 300 50
--Daily traffic volume (logging trucks)	First - - 3 Second - - 3 0	First - - 20 Second - - 20 0	First - - 200 Second - - 200 0
--Cumulative 18-kip ESAWL	0 First 18,500 Second 18,530	0 First 247,100 Second 247,130	0 First 3,706,600 Second 3,706,630
Annual routine maintenance cost per lane (dollars)	First - - 50 Second - - 50 0	First - - 200 Second - - 200 0	First - - 400 Second - - 400 0
*Annual routine maintenance cost per lane (dollars)	First - - 50 Second - - 50 0	First - - 100 Second - - 100 0	First - - 200 Second - - 200 0
*Number of MMBF of timber hauled	First 55	First 730	First 10,950
*Aggregate Surface loss (in./MMBF)	First 0	First 0.025	First 0.100

(Continued)

TABLE 3.1. LIST OF VARIABLES AND RANGES (CONTINUED)

Variable Name	** Low	Average	*** High
Minimum length first performance period-XTTO (years)	1	2	4
Minimum length second performance period-XTTO (years)	1	2	4
<u>Restriction Variables</u>			
Maximum funds available for initial construction ($)	100,000	150,000	200,000
Maximum allowable total thickness of initial construction (inches)	15.0	25.0	35.0
*Maximum allowable total thickness of initial construction (inches)	20.0	30.0	40.0
Minimum thickness of an individual rehabilitation (inches)	0.5	1.0	4.0
*Minimum thickness of an individual rehabilitation (inches)	2.0	3.0	4.0
Accumulated maximum thickness of all rehabilitations (inches)	10.0	12.0	15.0
*Accumulated maximum thickness of all rehabilitations (inches)	12.0	16.0	20.0
Maximum thickness of an individual rehabilitation (inches)	2.0	4.0	6.0
*Maximum thickness of an individual rehabilitation (inches)	4.0	4.0	4.0
*Minimum thickness of top layer (inches)	2.0	4.0	6.0

(Continued)

TABLE 3.1 LIST OF VARIABLES AND RANGES (CONTINUED)

Variable Name	** Low	Average	*** High
Parameter Associated with OL and Road Geometrics			
Distance over which traffic is slowed in the lane in which rehabilitation occurs-XLSO (miles)	0.25	0.50	1.00
Distance over which traffic is slowed in the opposite lane from the rehabilitation-XLSN (miles)	0.25	0.50	1.00
Width of the base (feet)	26.0	26.0	26.0
*Width of the base (feet)	28.0	28.0	28.0
Slope of the base	1	2	3
Percent of ADT which will pass through rehabilitation-PROP	2.0	6.0	10.0
Parameters Associated with Traffic Speeds and Delays			
Vehicles stopped by construction equipment, rehabilitation direction-PP02 (%)	0	5	10
Vehicles stopped, non-rehabilitation direction-PPN2 (%)	0	5	10
Average delay per vehicle due to equipment, rehabilitation direction-DDN2 (hours)	0.0	0.1	0.3
Average delay per vehicle due to equipment, non-rehabilitation direction-DDN2 (hours)	0.0	0.1	0.3
Average approach speed to the rehabilitation-AAS (mph)	20	30	50
Avg. app. speed through the rehabilitation-ASO (mph)	10	20	30
Average speed through rehabilitation area, non-rehabilitation direction-ASN (mph)	20	30	50

(Continued)

Table 3.1 LIST OF VARIABLES AND RANGES (CONTINUED)

Variable Name	** Low	Average	*** High
<u>Grading or Seal Coat Considerations</u>			
Number of passes grader or seal coat truck makes on the section-NGRSC	2	3	4
Average speed of grader or seal coat truck-ASGRH (mph)	20	10	5
Distance grader moves before letting cars behind it pass-GRDIS (miles)	0.5	1.0	2.0
Average speed of trucks in grading or seal coat direction-ASOTR (mph)	20	10	5
Construction cost of seal coat-SC ($/lane mile)	1,000	1,500	2,000
* Construction cost of grading-SC ($/lane mile)	50	100	200
Time between seal coat-TBSC (years)	10.1	5.0	3.0
Time between gradings-TBG (years)	0.33	0.25	0.17
<u>Vehicle Operational Cost</u>			
Average operating cost for vehicles other than logging trucks ($/mile)	0.1	0.3	0.6
Average operating cost for logging trucks ($/mile)	1.0	1.5	2.0

(Continued)

TABLE 3.1 LIST OF VARIABLES AND RANGES (CONTINUED)

Variable Name	** Low	Average	*** High
Construction Materials and Properties			
In-place cost per compacted cubic yard (dollars)			
--Paved: Top Layer	50.00	35.00	25.00
--Paved: Second Layer	20.00	12.00	8.00
--Paved: Third Layer	10.00	7.00	4.00
--Unpaved: Top Layer	20.00	12.00	8.00
--Unpaved: Second Layer	10.00	7.00	4.00
Layer coefficient			
--Paved: Top Layer	0.45	0.30	0.20
--Paved: Second Layer	0.20	0.15	0.10
--Paved: Third Layer	0.15	0.10	0.05
--Unpaved: Top Layer	0.20	0.15	0.10
--Unpaved: Second Layer	0.15	0.10	0.05
Soil Support Value (Subgrade)	6.0	4.0	2.0
Soil Support Value			
--Paved: Second Layer	9.6	8.6	7.6
--Paved: Third Layer	8.0	6.8	6.0
--Unpaved: Second Layer	8.0	6.8	6.0
Salvage Value (dollars)			
--Paved: Top Layer	70	50	30
--Paved: Second Layer	100	50	25
--Paved: Third Layer	100	50	25
--Unpaved: Top Layer	100	50	25
--Unpaved: Second Layer	100	50	25

From Table 3.1, it can be seen that there are some variables having the same arithmetic value for low, average, and high level. Examples are the total number of materials available, width of each lane, number of lanes, and model for describing the traffic delay pattern. Obviously, those variables were not analyzed. It was decided to fix them at some average or mean value from the beginning of the study, in order to maintain the same highway classification.

Asphalt Concrete Paved Roads - Average Level. For this particular condition, one variable was selected (following an order previously listed in Table 3.1 and according to the order in the User's Manual) and solutions were run at the selected variable's low value and high value with all the other variables fixed at the average level.

After the sensitivity analysis for this level was completed, it was found that 20 variables out of 49 had significant effect on the total overall pavement cost. Of those 20 variables, there were 15 with the most significant effect, showing a difference between \$88,000 per mile and \$3,400 per mile (when low and high value of the variable were used). For the condition with all variables at the average level the optimum pavement design cost \$105,250 per mile for a three-layer design. The mentioned effect can be observed in more detail in Table 1 and Figs 1 through 5 in Appendix A.

Variables are listed below in descending order of sensitivity:

(1) traffic conditions,

(2) soil support value of the subgrade,

(3) regional factor,

(4) minimum thickness of an individual rehabilitation (OVMIN),

(5) salvage value of the top layer,

(6) annual routine maintenance cost,

(7) time between seal coats,

(8) salvage value of the second layer,

(9) material cost, layer coefficient and soil support of second layer,

(10) terminal serviceability index (P2),

(11) material cost, layer coefficient and soil support of top layer,

(12) swelling clay parameter (b_1),

(13) non deterioration parameter (P2P),

(14) material cost, layer coefficient and soil support of third layer,

(15) seal coat cost,

(16) salvage value of the third layer,

(17) interest rate,

(18) slope of the base,

(19) initial funds for construction,

(20) initial serviceability index, PSI,

(21) serviceability index after an overlay.

For variables ranking from 22 to 33, there was a small effect and they were not plotted. Most of these variables are grouped in parameters associated with overlay, road geometrics, traffic speeds, and delays (see Table 3.1). The rest of the analyzed variables did not show any effect.

As may be observed from Table 1 and Figs 1-5 in Appendix A, there are several variables which are necessarily coupled in order to obtain a larger effect. For example, material cost, layer coefficient, and soil support value for each layer are tied together because when one goes up, the others go up also. In other words, it is practical to relate a bad material with a low soil support value with a low layer coefficient and an inexpensive material. The same principle is applied for the opposite case. Design period and average daily traffic for non-logging trucks and for logging trucks are similarly related in order to apply the respective cumulative 18-kip ESAL.

Additional information was obtained by analyzing the computer execution time for this "average condition" performed on asphalt concrete paved roads. Table 1 in Appendix A shows the computer time for executing the program when the low value and high value of each variable are run and the rest are fixed at average values. Results are very interesting, especially for the 15 variables having the most significant effect on total cost of the project.

Considering the total execution time of 25.9 seconds when all variables are fixed at the average level, the traffic variables were the most significant, causing a difference of 190 seconds between low and high condition. Other variables that had a large or significant effect on computer time were soil subgrade support (88 seconds between low and high value), material cost and layer coefficient for the top layer (68 seconds), swelling clay parameter (27 seconds), regional factor (23 seconds), and minimum thickness of an overlay (20 seconds). The rest of the considered variables had only a small effect on computer execution time, with differences of 19 to 0.2 seconds. This information can prove valuable in determining which variables may be responsible for excess computer time.

Asphalt Concrete Paved Roads - Low Level. For this condition, a variable was selected and solutions were run at its average value with all the other variables fixed at a low value. It is important to note that this is an unusual condition, because it is not very common to design roads having such good conditions (i.e., very good soil support value of subgrade, good layer coefficients, low traffic, high PSI, low regional factor value, etc.).

It was determined that 14 out of 49 variables had significant effect on the total overall pavement cost for this condition. Of these 14 variables, there were 7 with the most significant effect, showing a difference between \$63,277 per mile and \$3,653 per mile. These effects can be observed in more detail in Table 2 and Figs 6-9 in Appendix A.

The variables for low condition are listed below, in descending order of sensitivity:

(1) traffic conditions,

(2) soil support value of subgrade,

(3) regional factor,

(4) interest rate,

(5) material cost, layer coefficient and soil support of third layer,

(6) annual routine maintenance cost,

(7) time between seal coats,

(8) salvage value of the second layer,

(9) material cost, layer coefficient and soil support of the top layer,

(10) salvage value of the top layer,

(11) slope of the base,

(12) salvage value of the third layer,

(13) seal coat cost,

(14) material cost, layer coefficient and soil support of second layer.

There was a small effect from variables having a rank from 8 to 14, with the remaining input variables not showing any effect.

The computer execution times for this condition are listed in Table 2 of Appendix A. Considering the small time required when all variables are fixed at low value (3.7 seconds), there were no significant differences found. The maximum was less than a second.

Asphalt Concrete Paved Roads - High Level. As noted for the analysis performed on paved roads for low level, the high level condition is also not a very common one. However, it is possible in some situations to be dealing with these "high" or too restrictive conditions. The high condition does not always imply that the variables have a high numerical value, but that they have a restrictive one, such as heavy and large traffic, poor soil support value, low layer coefficients, high regional factor, high maintenance cost, and so on. When this portion of the analysis was performed, one of the variables was selected and solutions were run at its low and average value, with all the other variables fixed at the high value.

Following the established order indicated in Table 3.1 and the User's Manual, several trials were carried out applying the sensitivity analysis principles of this study without obtaining results. It was found that feasible designs are not possible for the specified conditions when all variables are fixed at the high value. This generates a message printed in the computer printout which reads: "Construction restrictions are too binding. There are no feasible designs."

Based on the unsuccessful results, it was decided to analyze groups of variables which could possibly be modified to a "less restrictive condition." This did not follow the analysis format, since all variables were not set at their high values. However, it was hoped that some additional information could be derived from the altered procedure. A considerable number of computer runs were completed, resulting in few feasible designs but determining the following points:

(1) Designs had resulted in an excessive total overall cost.

(2) Computer time for execution was always large.

(3) It was required to alter some variables at the same time up to the low level (very good construction conditions).

(4) Resulting pavement structure was always excessively thick.

(5) Some input conditions risked the problem of putting the program into an "infinite loop."

Aggregate Surfaced Roads - Average Level. The analysis of aggregate surfaced roads at the average condition followed the same process as that applied for paved roads. One variable was selected and solutions were run at its low and high values with all the other variables fixed at the average values. It was decided to use a two-layer system on this type of road, so the number of input variables was reduced to 47 as a result of fewer materials inputs.

After the completion of this phase of the sensitivity analysis, the following was found. There were 24 out of 47 variables having significant effect on the total overall pavement cost. Of those 24, there were 16 showing the largest effect with a range in difference from $65,577 per mile to $3,181 per mile. A small effect was found for variables ranking 25 to 32, with the rest not showing any effect.

The variable sensitivity is listed below in descending order:

(1) traffic conditions,

(2) material cost, layer coefficient of the top layer,

(3) aggregate surface loss,

(4) soil support value of the subgrade,

(5) salvage value of the top layer,

(6) minimum thickness of an individual rehabilitation (OVMIN),

(7) grading cost,

(8) regional factor,

(9) material cost, layer coefficient and soil support of second layer,

(10) swelling clay parameter,

(11) interest rate,

(12) minimum length of the performance period (XTTO),

(13) slope of the base,

(14) accumulated maximum thickness of all rehabilitation (OVMAX),

(15) time between gradings,

(16) annual routine maintenance cost,

(17) terminal serviceability index (P2),

(18) average approach speed to the rehabilitation area (AAS),

(19) serviceability index after an overlay (P1),

(20) non-deterioration parameter (P2P),

(21) average speed through the rehabilitation area (ASO),

(22) percent of ADT which will pass through rehabilitation area/hr. (PROP),

(23) average speed of the grader (ASGRH),

(24) distance along center line over which traffic is slowed in the lane in which rehabilitation occurs (XLSO).

Significant effects may be observed in detail in Table 3 and Figs 10-14 in Appendix A.

The computer time comparison for executing the program can be observed in Table 3 of Appendix A. Considering the total execution time of 21.8 seconds when all variables are fixed at average levels, it was found the most significant variables had differences of 2, 4, 6, 10, 15, 17, 24, and 28 seconds between low and high runs. However, it is most important to mention the problem encountered when considering OVMIN (minimum thickness of an overlay). A difference of 231 seconds was found in execution time for OVMIN. When running the high value (4.0 inches) the program executed in 4.9 seconds. When running the average value (3.0 inches) execution time was 21.8 seconds. When running the low value (2.0 inches) execution time was 236.3 seconds. The importance of and problems found with variables such as this will be discussed later on, but it is convenient to comment in advance on what this result means.

With the maximum thickness of an individual rehabilitation (OVMAXL) four inches, the difference with OVMIN when the high value was used was zero, and execution time was minimum (4.9 seconds). The difference between OVMAXL and OVMIN when the average value was used was one inch, so execution time went up to 21.8 seconds. But, the difference between the same two parameters when the low value was used was two inches, causing time to go up to 236 seconds. This means that when the difference of OVMAXL-OVMIN goes up to one inch, the execution time is increased up to four times, but when that difference goes from more than an inch to two inches, the execution time is geometrically increased up to 60 times, resulting in excessive amounts of computer time. When a difference of three or more inches is used the result is an infinite loop and no designs. It is highly recommended that strict attention be paid to this when this significant variable is dealt with. Computer costs are directly related to program execution times, and substantial savings may be realized.

Failure Criteria Models

The latest LVR program version was modified in order to provide in the computer output additional information which was considered useful. Basically, this information shows the user how the computer is solving the program step by step, studying possible feasible designs inch by inch, beginning with the top layer input thickness and using second layer thicknesses until some design is feasible. Of course this process involves the minimum length of the performance period (XTTO) at each step. The output will show the time period for each failure model and the number of feasible designs on each trial. By observing the line when the first feasible design appears, the user can see which model has controlled it (Aggregate Loss, Rutting, and AASHTO Models).

Based on results obtained with this feature, Table 3.2 gives a summary of the most significant variables, the period of time to failure in years, and which model was controlling the design for both low and high values. It is interesting to notice how the Aggregate Loss Model was controlling almost 40 percent of the most significant variables, as listed in the next paragraph. The Rutting Model, as expected, controlled only the traffic characteristics. The AASHTO Model, in general, controlled 60 percent of the most significant variables and also variables having small effect.

Variables in which the Aggregate Loss Model controlled the design:

(1) material cost, layer coefficient, and soil support (top and second layers),

(2) soil support value of subgrade,

(3) regional factor,

(4) swelling clay parameter,

(5) minimum length of performance period.

TABLE 3.2. AGGREGATE SURFACED ROADS. SIGNIFICANT VARIABLES. FAILURE MODEL CRITERIA RESULTS.

Condition: Average Type: Aggregate Surfaced Roads

Sensitivity Analysis Variable	LOW (Time to Failure) (Years) AGG RUT AASH	Model of Failure Controlling XTTO = 2	HIGH (Time to Failure) (Years) AGG RUT AASH	Model of Failure Controlling
All variables fixed at average level	1-Layer Design 2-Layer Design	7.67 0.58 2.00 2.19 0.73 2.09 (years)		AASHTO AASHTO
Traffic	- 0.17 2.13 7.27 2.42 9.19	AASHTO RUT	No feasible designs Too restrictive	- -
Material Cost Layer Coefficient Soil Support of Top Layer	4.38 0.66 2.00 2.19 2.54 3.66	AASHTO AGG	Too restrictive 5.48 0.49 2.00	- AASHTO
Aggregate Surface Loss	- 0.73 2.78 - 0.42 2.03	AASHTO AASHTO	No feasible designs Too restrictive	- -
Soil Support Value of Subgrade	2.19 2.33 1.06 2.19 11.96 5.22	AGG AGG	Too restrictive 5.48 0.03 2.00	- AASHTO
Salvage Value of Top Layer	7.67 0.58 2.00 2.19 0.73 2.09	AASHTO AASHTO	7.67 0.58 2.00 2.19 0.73 2.09	AASHTO AASHTO
OVMIN	This information not printed on output	- -	7.67 0.58 2.00 2.19 0.73 2.09	AASHTO AASHTO

(Continued)

TABLE 3.2. CONTINUED

Condition: Average Type: Aggregate Surfaced Roads

Sensitivity Analysis Variable	LOW (Time to Failure) (Years)			Model of Failure Controlling XTTO = 2	HIGH (Time to Failure) (Years)			Model of Failure Controlling
	AGG	RUT	AASH		AGG	RUT	AASH	
Grading Cost	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO
Regional Factor	5.48	0.13	2.00	AASHTO	Too restrictive			-
	2.19	0.73	3.16	AGG	4.38	2.20	2.00	AASHTO
Material Cost Layer Coefficient Soil Support of Second Layer	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	2.96	4.16	AGG	4.38	0.46	2.00	AASHTO
Swelling Clay Parameter	7.67	0.58	2.86	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	3.34	AGG	2.19	0.73	2.03	AASHTO
Interest Rate	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO
XTTO Low = 1.0	5.48	0.13	1.00	AASHTO	8.77	1.10	4.00	AASHTO
High = 4.0	1.10	0.36	1.47	AGG	4.38	2.20	4.00	AASHTO
Slope of the Base	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO
OVMAX All Rehabilit.	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO
Time Between Gradings	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO

(Continued)

TABLE 3.2. CONTINUED

Condition: Average Type: Aggregate Surfaced Roads

Sensitivity Analysis Variable	LOW (Time to Failure) (Years)			Model of Failure Controlling XTTO = 2	HIGH (Time to Failure) (Years)			Model of Failure Controlling
	AGG	RUT	AASH		AGG	RUT	AASH	
Annual Routine Maintenance Cost	7.67	0.58	2.00	AASHTO	7.67	0.58	2.00	AASHTO
	2.19	0.73	2.09	AASHTO	2.19	0.73	2.09	AASHTO

Difficult Variables

One of the important objectives of this study was to find information on problem variables in order to assist the user working with them. The most significant variables, those having the largest effect on total overall cost, were always associated with some kind of problem. For example, the minimum thickness of an individual rehabilitation (OVMIN) caused major problems with execution time and also had one of the most significant effects on aggregate road costs. It is very important to carefully determine values for this variable because of the large effect it has on cost ($13,000 per mile difference when varying only from two to four inches). It should be noted that a warning message in the original version of the User's Manual recommends a maximum difference of seven inches (aggregate roads) between OVMIN and OVMAXL.

The traffic condition variables, which, for simplicity, are considered as one variable here, were of particular importance. This variable (design period, ADT logging and non-logging trucks, and 18-kip ESAL) always had, for every analyzed condition or level, the number one ranking. This means it had the most significant effect among all variables. When dealing with these characteristics, the designer has to be aware of the significant effect on cost ($88,000 per mile difference when varying from low to high values). For this reason, traffic must always be analyzed in detail. Traffic was also responsible at times for there being no feasible designs for aggregate surfaced roads, due to a too restrictive condition when the high value was run. For computer time when executing the program, traffic also had large effects, as demonstrated for paved roads (differences from 27 to 216 seconds). These all explain why careful attention has to be paid to this variable.

Soil support value of the subgrade, regional factor, material cost, layer coefficients, soil support of layers, swelling clay parameters, and aggregate surface loss are also variables having a large effect on costs and differences in execution time, so it is advisable to spend more time with them when using and designing with the LVR program.

There is an additional variable which has some problems, XTTO (minimum length of performance period). At one stage of the analysis, there was a problem with this variable because of the interaction with the swelling clay parameter. It was found that XTTO becomes critical when a high value is used for swelling clay (i.e., 0.12). Also, the greater the length of the period, the larger the problem. Based on the outcome it was decided to gradually reduce XTTO. However, the shorter time periods resulted in longer execution times, and, as a warning, when XTTO is reduced to zero the computer will stay in an "infinite loop." For this reason, a warning message will be printed in the User's Manual establishing a new default value for this variable: XTTO = 0.1 year.

Conclusions and Recommendations

Based on the overall results obtained from performing this sensitivity analysis on asphalt concrete paved roads and aggregate surfaced roads, the following conclusions and recommendations are made.

Asphalt Concrete Paved Roads

(1) When dealing with the asphalt paved roads design, the user should give more time and attention to the following variables, the ones which have demonstrated the most significant effects:

	ranking:
Traffic variables	1
Soil support of the subgrade	2
Regional factor	3
Minimum thickness of an individual rehabilitation	4
Salvage value of different layers	5,8,16
Annual routine maintenance cost	6
Time between seal coats	7
Material costs, layer coefficients, and soil support values of top layer	11
second layer	9
third layer	14
Terminal serviceability index (P2)	10
Swelling clay parameter	12
Non-deterioration parameter (P2P)	13
Seal coat cost	15

Interest rate	17
Slope of the base	18
Initial funds for construction	19
PSI and SI after an overlay	20

It is also advisable to give additional attention to the variables having a rank of 1, 2, 3, 4, 9, 11, 12, 13, and 14 due to the large effect on computer execution time. Based on these results, the variables having only a small effect on the final answer (those variables with a rank of more than 20) should be fixed by the user at a mean value. After one or two years, when the program has been used enough to verify these results, those variables with a small sensitivity will be fixed at a mean value in the program.

(2) When the analysis was performed for low level (solutions run at average and high values, rest fixed at low), it was found that seven variables had the most significant effect, basically the same as the sensitive variables found for the average level, with only a small difference in the ranking weight. Computer execution time did not show any effect.

(3) From results obtained when the high level was performed, there are no specific conclusions, except those observations listed in the respective analyses.

Aggregate Surfaced Roads

(1) The following variables have demonstrated the most significant effect on the total overall cost, so attention should be given to them.

	ranking:
Traffic variables	1
Material costs, layer coefficients and soil support of top layer and second layer	2,9
Aggregate surface loss	3
Soil support value of subgrade	4
Salvage value of top layer	5
Minimum thickness of an individual rehabilitation	6
Grading cost	7
Regional factor	8
Swelling clay parameters	10

Interest rate	11
Minimum length of performance period (XTTO)	12
Slope of the base	13
Accumulated maximum thickness of all rehabilitation	14
Time between gradings	15
Annual routine maintenance cost	16
Terminal serviceability index P2	17
Average approach speed to rehabilitation (AAS)	18
PSI and SI after an overlay	19
Non-deterioration parameter (P2P)	20
Average speed through the rehabilitation (ASO).................	21
Percent of ADT during construction (PROP)......................	22
Average speed of grader (ASGRH)................................	23
Distance traffic slowed (XSLO).................................	24

As can be observed, these variables are basically the same as those with significant effects on paved roads, with some additional ones involved in aggregate roads only, such as aggregate surface loss, grading cost, time between gradings, and minimum length of performance period. It is also recommended that additional attention be given to variables having a rank of 1, 2, 3, 4, 6, 8, 9, 10, 12, 14, and 15 due to the largest effect on execution time, especially when dealing with OVMIN and OVMAXL. Based on these results, the user should fix at a mean value the variables having only a small effect on the final answer (those variables with rank higher than 24).

(2) Concerning the failure criteria models, it was found that the Rutting Model controlled traffic conditions. The Aggregate Loss Model controlled material costs, layer coefficients, soil support values of different layers, soil support value of the subgrade, regional factor, swelling clay parameter, and minimum length of performance period. The AASHTO model controlled the rest of the variables dealing with the LVR program.

<u>Problem Variables</u>. As a general rule the variables having the most significant effect on total cost and computer execution time deserve special attention in order to avoid or minimize problems, as discussed during the analysis. It was also recognized that there are several too restrictive values in some variables for the specified construction conditions; therefore, the user has to spend more time when characterizing them.

These are the problem variables:

(1) minimum thickness of an individual rehabilitation (OVMIN),
(2) maximum thickness of an individual rehabilitation (OVMAXL),
(3) traffic variables,
(4) minimum length of performance periods (XTTO),
(5) swelling clay parameter (b_1),
(6) regional factor,
(7) materials cost,
(8) layer coefficients,
(9) soil support values (specially for subgrade),
(10) aggregate surface loss,
(11) time between gradings or seal coats.

RUTTING PREDICTION MODEL

Because of the uncertain performance of the Rutting Model currently used by the Forest Service for predicting failure of aggregate surfaced roads from rutting, a study was conducted by the project staff in order to determine the accuracy of the model.

The Rutting Model currently used by the Forest Service is based on test data collected for aggregate surfaced airfields by the U. S. Army Corps of Engineers (Ref 5). The original Rutting Model related the time at which failure occurs with a total number of 18-kip equivalent single axle loads. This resulted in the following equation (see also Equation 12 of the Phase II Final Report):

$$\text{Log } Wt_{18} = \frac{t}{0.216\sqrt{\frac{1111.1}{CBR} - 35.81}} - 0.789 \qquad (1)$$

where

Wt_{18} = Total number of 18 kip equivalent single axle load applications required to produce a two-inch rut depth (by Ron Williamson, U.S. Forest Service).

t = the thickness of the surface material over the subgrade (inches) having a layer coefficient of 0.14.

Later, because of problems concerning these constants, it was recommended in a Technical Memorandum (Appendix E) that the thickness model used in LVR be changed to

$$\text{Log } Wt_{18} = \frac{t}{0.176\sqrt{\frac{1111.1}{CBR} - 35.81}} - 0.682 \qquad (2)$$

The reason for recommending these new constants was that the previous model probably overdesigned for rut depth, as shown later in the text.

At the same time, a new Rutting Model was introduced as a reasonable method to predict rut depth in flexible pavements (Ref 6). This method was developed by C. L. Monismith for the U.S. Forest Service to be used in the design of pavements of low-volume roads.

The approach used by the project staff to carry out this study was to compare predictions from the Rutting Models (Forest Service Model and Monismith's Model) with actual field measurements. Based on AASHO Road Test data for rut depth, which was produced under known number of applications, load, and characteristics of materials, three examples were chosen to show the variation of both the Forest Service Model and that developed by Monismith with respect to the AASHO Road Test data.

The modified Forest Service Model (Eq 2) was used for this study, in addition to Monismith's model (Ref 6); in it the necessary forms of constitutive relationships provide a means of estimating permanent deformation from repetitive loads. In summary, the steps followed for this comparative study were:

(1) Select three pavement structures at AASHO Road Test with a minimum thickness of surface layer since rut depth data were not available for unpaved roads.

(2) Convert the selected pavement structures to aggregate structures. To do this, convert the surface layer to base material based on the original structural number from AASHO data.

(3) Collect all the available data on the characteristics of the material and traffic conditions used during the AASHO test, and record the amount of rut depth produced under those conditions.

(4) Using the Forest Service Model, and based on the structural characteristics and CBR values of the subgrade, calculate the required number of Wt_{18} applications to produce a two-inch rut depth for every example.

(5) Determine the rut depth that would be produced by applying Monismith's model to each of the examples, by using the material characteristics and number of Wt_{18} applications which produced the known rut depth, as collected by AASHO.

(6) Plot the performance in terms of rut depth produced under certain numbers of Wt_{18} applications for each of the structures and for each model; likewise plot the known performance from the AASHO data in the same terms.

For the first example, a structure was picked which consisted of one-inch asphalt concrete, six-inch base material, and four-inch subbase material. The one-inch asphalt concrete was then converted to a base material based on the structural number of the pavement.

$$\overline{SN} = (0.44 \times 1) + (0.14 \times 6) + (0.11 \times 4) = 1.72$$

For converting the surface asphalt concrete to base material the following equation was used:

$$1.72 = 0.14t + (0.11 \times 4)$$

where,

$$t = \frac{1.28}{0.14} = 9.1 \quad \simeq \text{9-inch base material}$$

By applying the Forest Service Model, Monismith's Model, and the AASHO data various rut depths were obtained. These are shown in Fig 3.3 as a function of number of Wt_{18} applications. To help visualize the comparison between models, the inset in Fig 3.3 shows the predicted rut depths for each model versus measured rut depths under the same number of Wt_{18} applications, using AASHO's data as the line of equality. Likewise, two other examples with different structural characteristics were solved. The results are shown in Figs 3.4 and 3.5.

Discussion of Model Performance

From the previous figures the following conclusions may be noted:

(a) The greater the numbers of Wt_{18} applications and relatively greater structural numbers, the greater the similarity between the rut depth performance curves of AASHO data and Monismith's method (Figs 3.3 and 3.4).

(b) The lower the numbers of Wt_{18} applications and lower structural numbers, the greater the difference between Forest Service Model and AASHO data and Monismith's method (Fig 3.4). This conclusion may be considered of singular importance, since, based on a relatively weak structure in Fig 3.4, the number of Wt_{18} applications required to produce a two-inch rut depth is too low (140) using the Forest Service Model. It could take, say, one week to accumulate that number of applications. Even though the structure consists of a nine-inch base material laid on a subgrade of three CBR value, certainly the structure would not experience that rut depth in such a short time.

(c) Since for a low structural number the required number of Wt_{18} applications to produce a two-inch rut depth by the Forest Service Model is very small compared to that by AASHO data and Monismith's method, the Forest Service Model probably over-designs aggregate roads.

It is important to note that, for whatever conclusions may be made from these examples, the following limitations should be taken into consideration:

(1) Because of the lack of data from the AASHO road test concerning rut depth on aggregate roads, the data in this study were derived by converting paved roads to those for aggregate roads. In doing this, the surface layer thickness was converted to its equivalent in base material based on the original structural number from AASHO data.

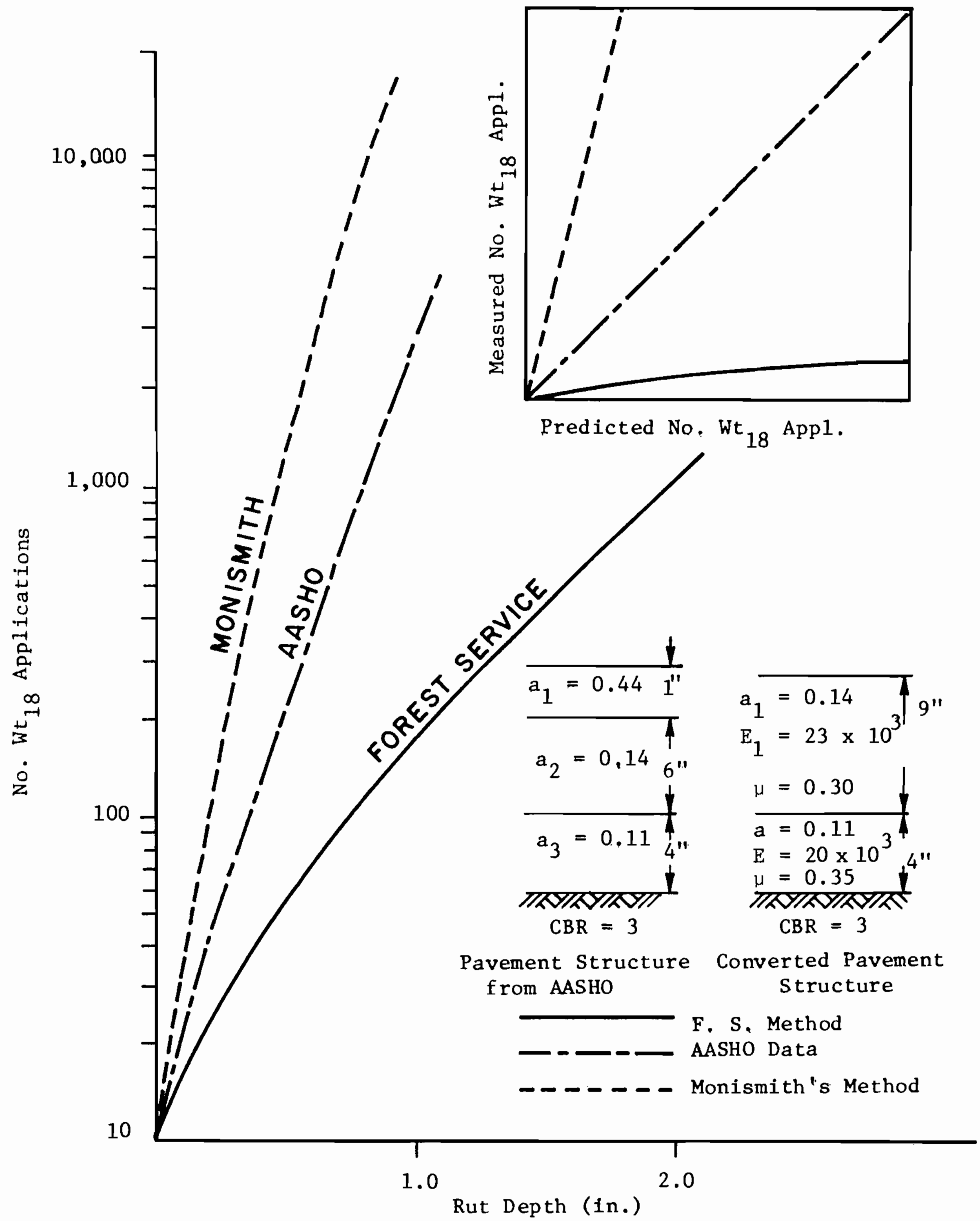

Fig 3.1. Rutting model comparisons.

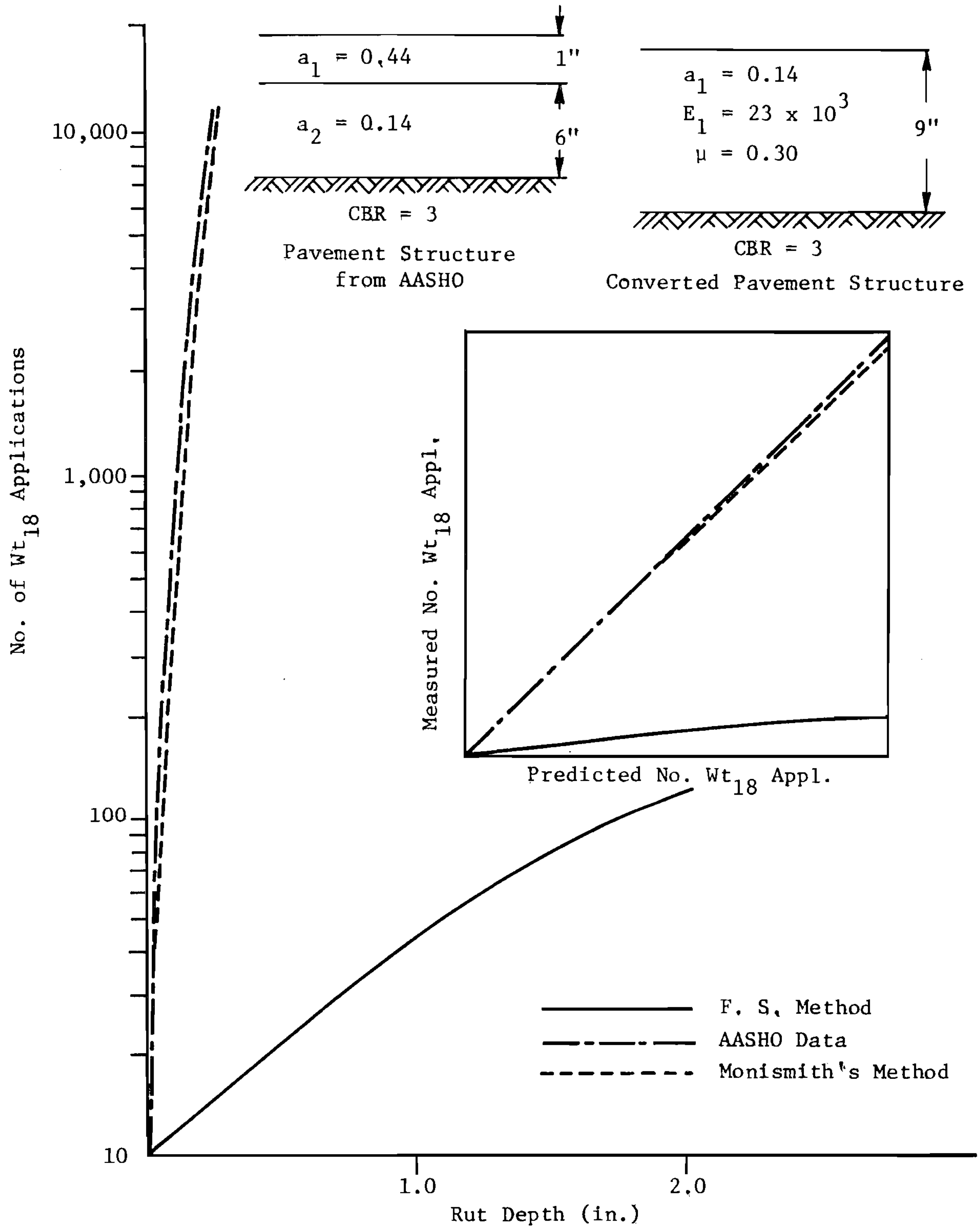

Fig 3.2. Rutting model comparisons.

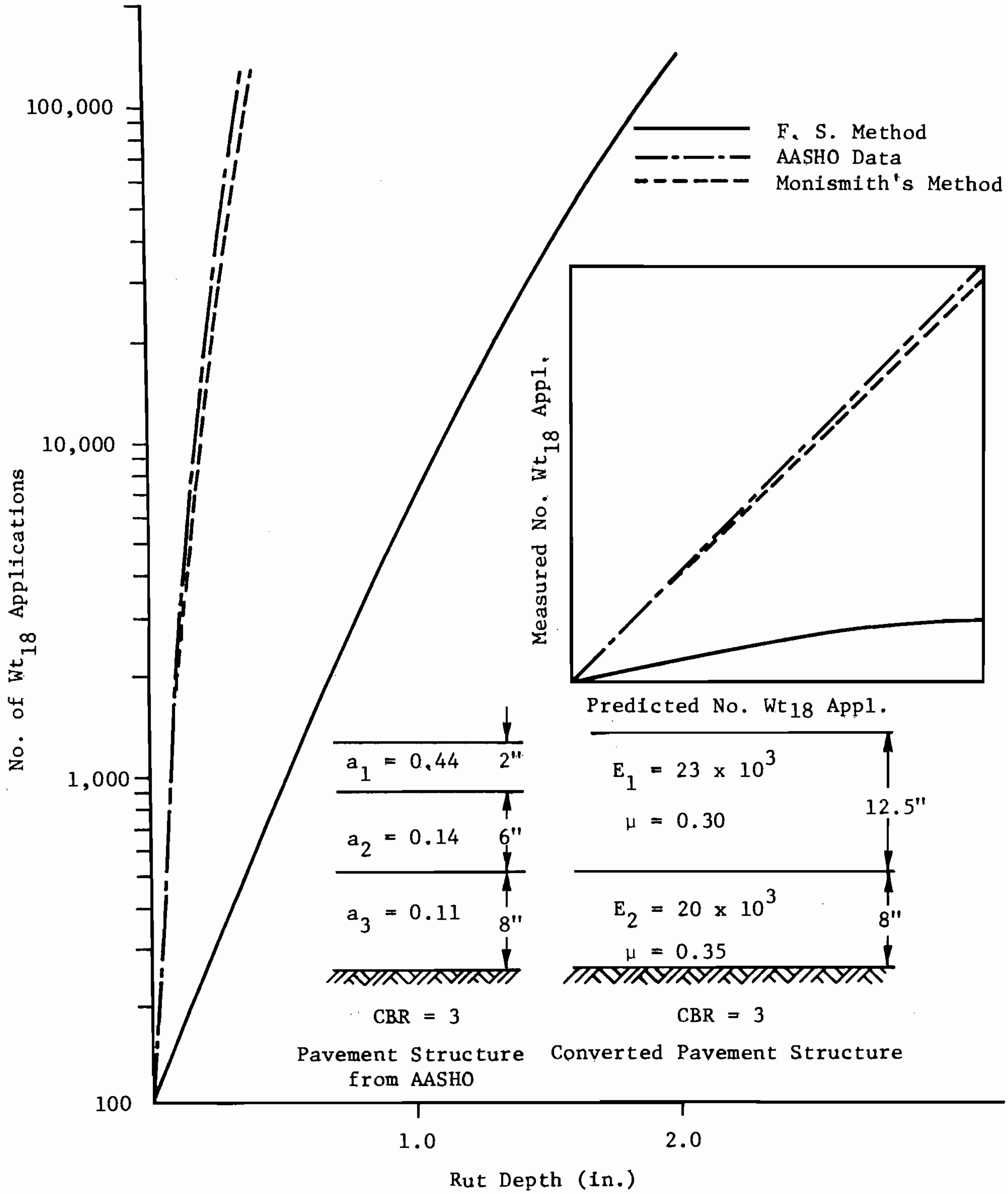

Fig 3.3. Rutting model comparisons.

(2) Although the properties of the materials used in Monismith's model are almost the same as those found by AASHO, it was not possible to avoid some assumptions concerning the properties of the base material.

Finally, even considering the limitations of this study, there appears to be enough basis to conclude that a more realistic Rutting Model is needed, or perhaps some improvements on the current Forest Service Model.

PROCEDURE FOR DETERMINING AGGREGATE LOSS

Loss of surfacing material due to the action of traffic is one of the three failure criteria that LVR uses to select initial designs and rehabilitation strategies for aggregate surfaced roads. Unfortunately, the models which have been developed for predicting this kind of deterioration have been shown to be less than adequate, either because the traffic data were not fully characteristic of Forest Service roads or because other factors, such as relative compaction and widening of the road due to grading, were not considered. As a result, the user of LVR is given considerable freedom in determining how aggregate loss is to be computed by the program.

The recommended approach is to input aggregate loss directly by specifying for each time period an amount of timber hauled in millions of board feet (MMBF) and a corresponding rate of loss in inches/MMBF. These values are multiplied together and the resulting quantity of loss is proportioned over the time period according to the rate of truck traffic, which is another time-dependent variable input by the user. Since the amount of timber hauled is used only in the computations of aggregate loss, the user can increase the amount hauled to account for aggregate losses due to recreational traffic, if they are known. In addition, the user has the option of specifying an additional constant rate (inches per year) of aggregate loss due to erosion.

An early version of LVR incorporated a loss prediction model developed by the Transport and Road Research Laboratory of England based on data acquired in Kenya (Ref 11). In the Kenya model, the aggregate loss is a function of traffic volume, annual rainfall, percentage gradient of the road, and the characteristics of the road surfacing materials. Even though the

Kenya study did not incorporate forested areas, some Forest Service engineers felt that it may be applicable to U. S. forest roads, especially in areas with relatively large volumes of recreational traffic. It was recognized, however, that because roads in this study had traffic consisting of primarily light vehicles and the data were clearly distinct from those for roads supporting heavy logging operations, that a different model was needed. As a result, the Kenya model was replaced by one developed by John Lund (Ref 12) on studies made in south-central Oregon. The Lund model, which has been available as an option in LVR during the implementation phase, uses the following equation:

$$GL = 0.162 + .0188(LT) + 0.0382(F/C) - 0.0011(TTU) - 0.00213(P3/4)$$

where

GL = aggregate loss in feet (corrected for settlement of subbase),

LT = number of loaded logging trucks in thousands,

F/C = fill or cut section (fill = 1.0, side cast = 1.5, cut = 2.0),

TTU = total traffic units in thousands (one non-truck = 2 units, one logging truck round-trip = 10 units), and

P3/4 = percent of material less than 3/4 inch in diameter.

Although sufficient to explain 79 percent of the variation in 16 sample road sections in southern Oregon (Winema, Rogue River, and Fremont NF), the equation is clearly not applicable to all Forest Service roads. For example, in one set of data prepared by personnel in Region 1, the amount of non-truck traffic (27 ADT) was large compared to the amount of logging trucks (5.5 ADT). The Lund equation, in effect, reduced to $GL = .006 - .003(LT)$ and thus predicted a negative rate of aggregate loss throughout most of the 20-year analysis period.

Realizing the limitations of this preliminary study, John Lund gathered additional data in Gifford Pinchot National Forest during the two-year period, 1973-1975 (Ref 13). Here it was found that relative compaction of the surfacing material (as determined by AASHTO T-99 procedures) was the most important variable affecting surfacing loss while traffic appeared to have much less correlation with it than in the original study. However, Lund noted that the traffic and timber volumes were lower and that there was some question about the reliability of the traffic data. His conclusion was that the southern Oregon study provided a more valid relationship between surfacing loss and traffic.

Until a better model is available, the LVR program will employ (as an alternative to the direct-input option) a loss-prediction equation involving truck traffic alone as the independent variable:

$$GL = .01 + 0.01019(LT)$$

This equation is provided by John Lund and is based on a two-year study of 16 surveyed sections in southern Oregon. It should be noted that only 56 percent of the variation in loss is explained by the equation and that less than 46 percent is explained when two sections that supported trucks with unusually heavy loads are deleted from the sample.

Efforts to develop a better aggregate loss prediction model are continuing at the University of Texas, although very little data on this subject are available. Some recent research done by others seems to indicate that non-truck (or recreational) traffic is more directly related to aggregate loss than truck traffic. These relationships will be investigated as model developments continue.

CHAPTER 4. ANALYSIS OF LVR IN USE

INTRODUCTION

The basic purpose of a low-volume road management program (LVR) is to allow the designer to identify the most economical pavement strategies, taking into consideration both initial construction and subsequent costs related to road maintenance and vehicle operation. In this way the designer is able to make the most efficient use of available resources, in addition to having a tool for predicting pavement performance for planning purposes. With the use of the model, he is also able to more carefully make important economic analyses which may affect the pavement strategy. For example, the Forest Service user can determine if an additional investment to increase the quality of the roadway will be offset by a higher price received for the timber; i.e., if the buyer is able to reduce his hauling costs he can, therefore, afford a higher timber price.

Before the initiation of this project, there was no systems management capability in the Forest Service for the type of analysis mentioned above. Chapter 50 of the Forest Service Transportation Engineering Handbook (Ref 14) is used for design of bituminous and aggregate surfaced pavements but has no pavement management information included in it. This chapter will investigate the use of LVR as a working pavement management system for Forest Service roads.

CAPABILITIES OF THE PROGRAM

The pavement management system consists of a single computer program, identified as LVR, that can be used to design both bituminous surfaced and aggregate surfaced roads. The user inputs relevant information and certain constraints, such as the number of layers in the pavement, the type of material for each layer, unit prices, total available construction funds, and minimum time to first overlay. The program will first compute initial construction designs that satisfy the given constraints and have a life expectancy greater than the minimum time to the first rehabilitation. Rehabilitation schedules for all initial designs are considered, in order to find the most economical strategy for that design. After computing all alternative strategies within the constraints, the model will print out the 40 most economic designs in ascending order by total cost (Fig 4.1). The total cost is calculated on a net present value basis from the following:

(1) initial construction costs
(2) seal coat costs for bituminous surfaced roads or grading costs for aggregate surfaced roads
    (a) materials, equipment, and labor costs
    (b) user delay costs
(3) minor maintenance costs
(4) rehabilitation costs (overlays for bituminous surfaced roads or aggregate addition and grading for aggregate surfaced roads)
    (a) materials, equipment, and labor costs
    (b) user delay costs
(5) vehicle operating costs
(6) salvage value costs

A detailed examination of LVR, and the different models that make up the program, is contained in the Phase II Final Report (Ref 2).

FOREST SERVICE APPLICATIONS OF LVR

LVR is a natural asset to the forest engineer who is interested in maximizing the benefits of a forest pavement while working within constraints of materials and cost. LVR allows the use of many kinds of constraints and decision criteria, which leads to various optimization techniques that can pick out favorable alternatives and simplify the final decision process.

Because of the large number of roadway miles under Forest Service jurisdiction, LVR may also be an important tool in evaluating management

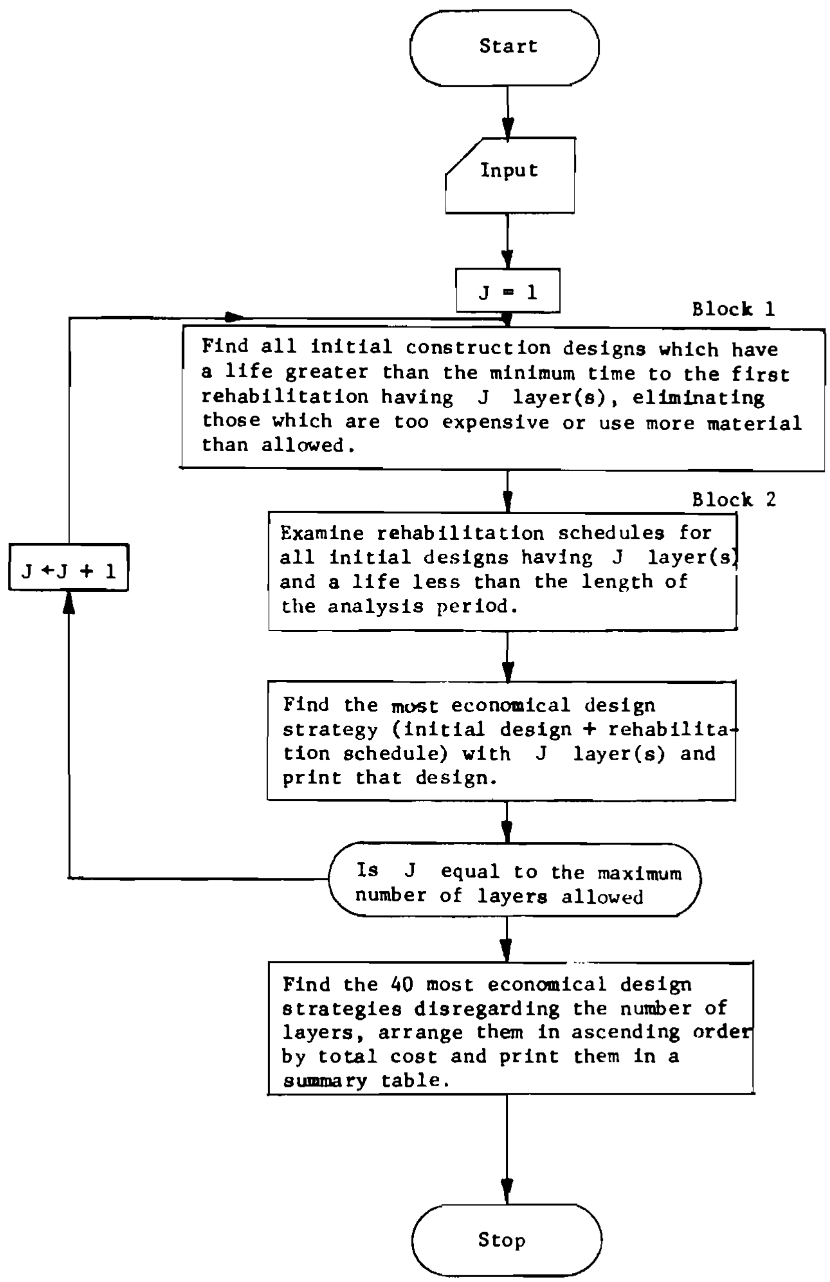

Fig 4.1. Conceptual flowchart of program LVR.

strategy and financial planning. The pavement management system allows the predicted performance characteristics of the pavement to be used to predict future financial needs and manpower requirements. In many cases expenditures are based on immediate needs, and there is little opportunity to establish long-range plans. As a result there may be no funds for upgrading when a pavement deteriorates below a certain level. In other years, there may be funds for a pavement that does not require upgrading. The capability to optimize the expenditure of available funds is obviously an important one.

Figure 4.2 shows graphically the concept of optimizing expenditures and other resources for a given number of projects (Ref 15). The figure shows a total of n projects, each requiring certain expenditures for construction and rehabilitation through time. By looking at any one year in the time scale, it is possible to observe the total required resources for all projects in that year. The schedule can represent all the sections of a roadway or the total system for a Region or Forest, depending on the situation. The use of such a diagram allows the Region or Forest Engineer to estimate the engineering manpower needs for design, construction supervision, and maintenance for a period of 15 to 20 years. If an unusual amount of manpower or financial resources will be required in a given year, plans to upgrade a given section of road can be rescheduled to give a more orderly distribution of available resources, thereby avoiding shortage during peak periods.

The ability to consider many constraints and variables during design, to optimize available funds and materials for construction, and to assist in management and financial planning are important characteristics of LVR which will be particularly beneficial to the Forest Service users.

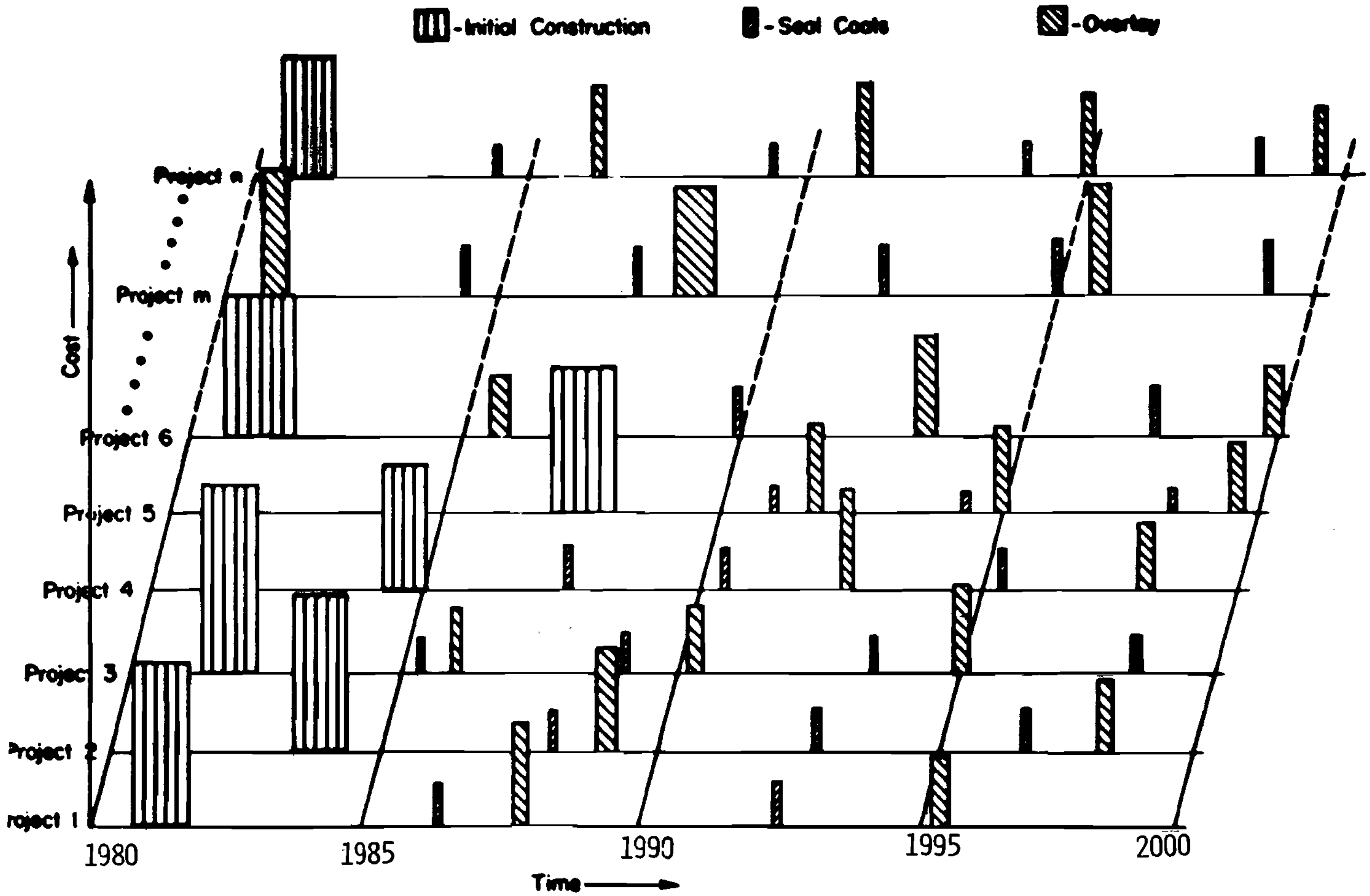

Fig 4.2. Schedule of work (Ref 11).

CHAPTER 5. PROPOSED PROGRAM REVISIONS AND RECOMMENDATIONS

INTRODUCTION

An important characteristic of a pavement management system is that it can continually be evaluated and updated, thereby allowing for improvement by having needed changes made in the models. Figure 5.1 illustrates this concept with different levels of model improvement after development. Level 1 is the initial computerization of the models in the system. The second level, which would be comparable to Phase III of the LVR project, allows for improvement of the models through sensitivity analyses, research, and implementation. Level 3 implements new or revised models which are the result of experience with the model. With more experience and improved data collection, stochastic applications are also considered to make the models more realistic in their performance. Level 4 then begins the changeover from empirical to mechanistic models, again as more experience and data collection make the need for changes apparent. The model is therefore constantly being changed, calibrated, and updated to give the user the best possible simulation of his particular conditions.

This chapter will list some of the LVR program revisions proposed by Forest Service users and University of Texas project staff, including recommendations for their use.

SYSTEM DATA BASE

It is necessary for the U. S. Forest Service to develop a system data base for collecting and organizing information pertinent to forest roads. No transportation system in the world involves low-volume roads, especially aggregate surfaced roads, on as large a scale as the Forest Service road system. Vital information regarding the performance of forest roads under different conditions of traffic, loads, climate, cost, materials, etc. can

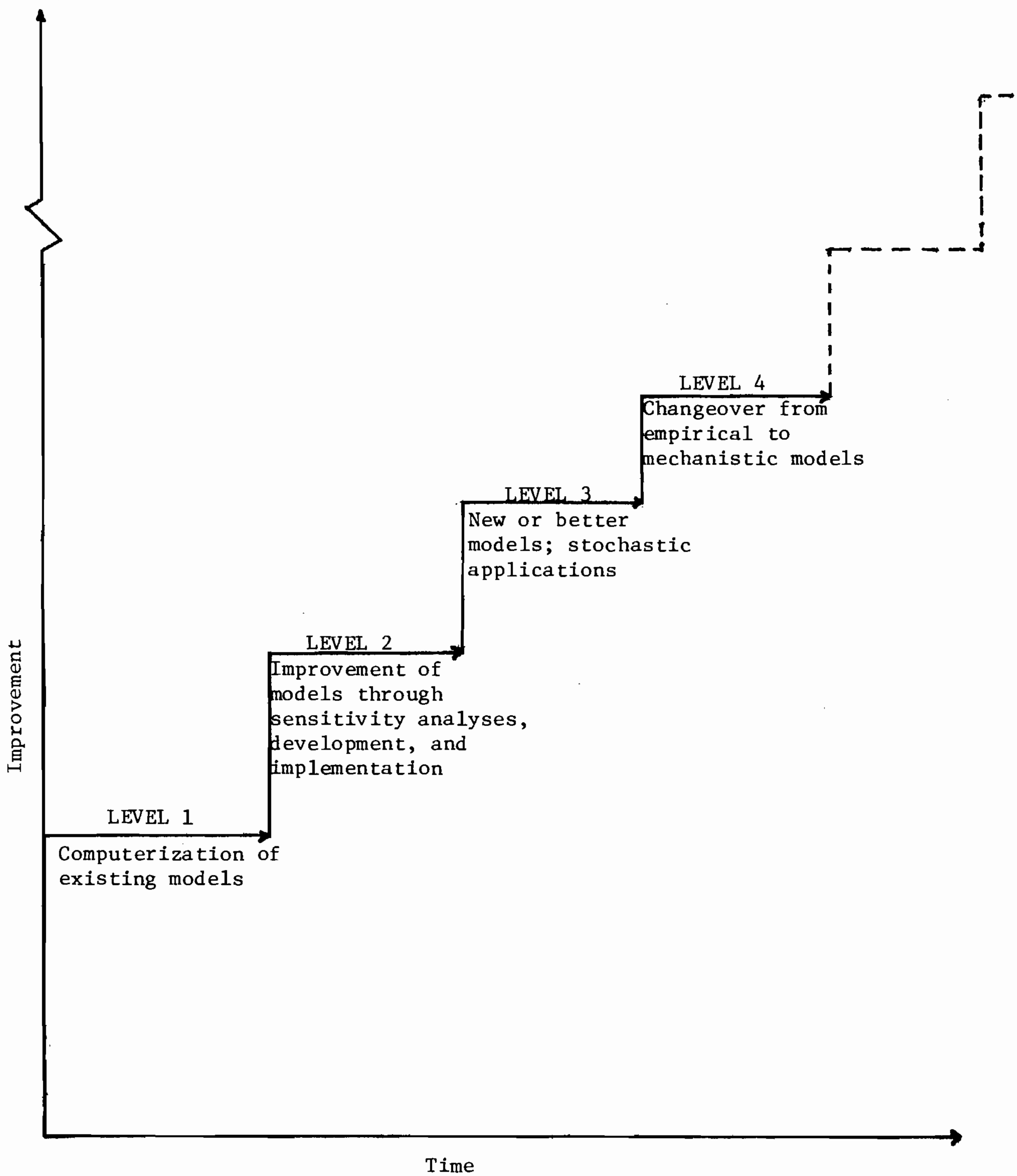

Fig. 5.1 Staged improvements of pavement management system

only be collected through efforts by the Forest Service.

A system data base would allow the Forest Service to gather information on pavement performance in an organized and beneficial manner. With the centralized Forest Service computer system that is now in operation, data could be organized and stored in an efficient manner. Because of Forest Service standardized procedure, data gathering could be confined to selected areas of interest such as aggregate loss, rut depth, pavement construction costs, pavement maintenance costs, vehicle operating costs, and pavement performance. With the information gathering process structured in such a manner, the problem of gathering too much unrelated or "worthless" data so common to transportation agencies could be avoided.

When the optimal strategy of a pavement design procedure is implemented, it may produce results different from those predicted. For this reason the system should be designed to include a sampling of information on every pavement of interest at each significant time step in the life of the pavement and at each major event in the life cycle of the pavement, such as an overlay or seal coat. A sampling procedure for such a data system must be developed so that significant changes in any of the variables in the pavement management system can be adequately assessed (Ref 15).

The benefits to be gained from a system data base are numerous. Direct information on pavement performance of forest roads is much more valuable than "converting" information from other studies which currently include gravel airports, African roads, and freeways in Illinois (AASHTO Road Test). Many valuable relationships may be discovered which can lead to more efficient and practical pavement management methods. Such a system data base would also provide information for calibrating existing performance models, such as those contained in LVR. This would provide a means to effectively evaluate the accuracy of the models, and provide the necessary information to make improvements in the models.

VEHICLE OPERATING COSTS

A method for determing vehicle operating costs should be included in LVR. The basic operating cost data for different vehicle types could be obtained by using the model developed at the University of California (Ref 4).

This model simulates tire wear and fuel consumption as a function of road geometrics, road surface type, and traffic parameters and considers other operating costs as a function of time. Developments at the University of Texas indicate that regression equations of solutions generated by the University of California model are quite accurate. This would provide a less sophisticated but easier and more economical way for the program to calculate vehicle operating costs for the user. Another approach could be to develop a cooperative program with industry, where user cost data could be gathered and analyzed using regression techniques. This would allow input of user cost information into LVR which was based on experience from a certain type of roadway in a particular area. Certain large forest products corporations may now have significant data bases for these costs. Various transportation authorities, such as the Washington State Utilities Commission, should be surveyed to determine how they treat vehicle operating costs, particularly in relation to the logging industry.

INTERACTION WITH ROAD DESIGN SYSTEM (RDS)

Program LVR should be made interactive with RDS. The Forest Service Road Design System (RDS), which consists of a family of programs that handle geometric design and construction quantities, is presently being documented under a contract with the Forest Service. Once the documentation is complete, it will be advantageous to incorporate an interaction between RDS and LVR to achieve a more rational system. This would allow both the road geometrics and pavement to be designed considering the same resources and constraints, possibly with LVR generating template data for RDS. With the aforementioned developments in LVR of a feedback data system and a Vehicle Operating Cost Model, interaction with RDS would allow optimization of total resources and cost in a far more complete manner. The interacting effects of geometric alignment, construction quantities, vehicle user cost, and pavement design and maintenance should be considered together in one total concept optimal strategy.

PROPOSED REVISIONS FROM PHASE II

The following additions to LVR were proposed in the Phase II final report:

(1) A computer plotting option which will print the PSI versus time curve for the optimum design strategy.

(2) A deflection design method as an alternate to the other design models in the program. (A deflection design model was introduced to the system at the request of the Forest Service; however more development is necessary for a complete model). This is explained further in Appendix E.

(3) An operating cost versus PSI curve, in order to reflect how operating cost is affected by the overlay or gravel addition strategies considered in the candidate design. (Since substantial effort will be required, this item can be accomplished only if the data are developed independent of this study).

DECISION ANALYSIS CAPABILTIY

To develop a more realistic model, decision analysis capabilities should be included in LVR. The LVR pavement management system presently uses deterministic methods to analyze different parameters in the program. This indicates that even though all inputs have different amounts of reliability, all are treated with equal weight in the model and are assumed to be "known." In reality, the program inputs may vary from an estimate to a fairly precise known value. For this reason stochastic concepts should be introduced into LVR to allow decisions to be made more realistically. For example, particular inputs have different degrees of uncertainty, such as those dealing with traffic, material cost, regional factor, and discount rate. Using the principles of decision analysis probabilities could be associated with each of these inputs, depending on the user's knowledge about their reliability. Given probabilities for the inputs, the model could determine the probability of the associated outcomes. By assigning each outcome a relative value, or "utility," a decision can then be made by the user with the help of the model to select an optimum pavement strategy. This type of analysis is very important when the user is trying to take into consideration such factors as economic benefits from a particular roadway or is forecasting the future uses of a road.

CHAPTER 50 REVISION

In July 1978, the U. S. Forest Service and The University of Texas entered into a cooperative agreement to revise and improve Chapter 50 of the Forest Service Transportation Engineering Handbook. It was decided that, even though LVR is operating successfully in its present form, the basis of some models used in LVR are in Chapter 50 and that an improvement would update Chapter 50 and assist interaction with LVR. Specifically, the objective is to improve the Flexible Pavement Design Guide by making needed revisions and providing additional capabilities. To accomplish this objective the following tasks will be completed:

(1) Develop reliability factors for different classifications of roads. Provide the designer with flexibility in accordance with road's present and future classifications. Provide the means for a designer to select appropriate failure criteria for each specific project.

(2) Improve the Rutting Model using a more rational approach. Improve the Aggregate Loss Model in accordance with recent research and experience.

(3) Analyze the wheel load equivalencies for single and dual wheels for legally loaded and oversized loads as they presently appear in Chapter 50. Analyze recent information on structural layer equivalencies. Revise the wheel load equivalencies and the structural layer equivalencies in Chapter 50 in accordance with these analyses.

(4) Develop a procedure in Chapter 50 for determining the regional factor.

(5) Provide improved procedures for evaluating the amount, type, frequency, and distribution of traffic over the design life of the roadway surface.

(6) Provide a capability to consider the effects or non-effects of roadway drainage.

(7) Provide a deflection design alternate in Chapter 50.

(8) Analyze the findings from recent pavement and other appropriate research for low-volume roads. Incorporate those significant findings that are compatible with the basic approaches followed in Chapter 50. Such items as vehicle operating cost models and selected findings from the Brazil study associated with the University of Texas should be carefully scrutinized to determine their applicability and potential for enhancement of Chapter 50.

(9) Provide a comprehensive, interactive connection between Chapter 50 and the LVR computer program. Incorporate in Chapter 50 an up-to-date LVR user's manual with all appropriate discussion, instruction, figures, tables, and examples of input and output data. In addition, make the appropriate connections and referrals in the LVR user's manual with the revised Chapter 50.

(10) Check all figures, tables, nomograph charts, and other supporting material in Chapter 50 for correctness, accuracy, and ease of use. Make changes as needed. Completely rewrite Chapter 50, with an appropriate explanatory text to reflect all of the aforementioned changes, additions, and improvements.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The specific objective of Phase III of this study was to implement the LVR pavement management system on a trial basis in selected Regions of the Forest Service. As a result of this implementation, modifications in the program were to be made and documented, to assist in making LVR operational in standard Forest Service procedure. In this, the final report for Phase III, it can be seen that the project has been a successful one. The Forest Service now has a fully operational pavement management system program, referred to as LVR. It has been implemented in nearly all parts of the country, including far more users than had originally been anticipated. This trial usage, together with investigations by the project staff, led to modifications and improvements within the program and to recommendations for further development.

To accomplish these objectives, tasks were performed in several areas to facilitate the trial implementation. A sensitivity analysis was performed on the model variables to determine the effect of each on the total overall pavement cost. This information will allow the designer to concentrate on those variables which are most important in a particular situation and to fix other variables which are not sensitive to some average value. In order to effectively introduce Forest Service users to the LVR program, four training sessions were held which instructed 70 personnel from different Regions in operation and use of the program. This succeeded in expanding the trial implementation to additional users and more applications of Forest Service work than had originally been expected.

Many components of the program were investigated during the implementation. The Rutting Prediction Model was found to be conservative, and resulted in over-design of aggregate surfaced roads. Problems were discovered with the Aggregate Loss Model, and through interaction with Forest Service users it was suggested that this model be revised and improved. Vehicle operating costs and RDS interaction were also investigated at certain stages during the study. As modifications and improvements were made to the program, documentation of the models was updated to allow Forest Service computer personnel to more easily gain familiarity with the system. With changes in the program and suggestions from users, the User's Manual was continually updated to its final version, and published as a separate appendix to this report.

To determine the effectiveness of the trial implementation, Forest Service personnel across the country were contacted and answered questions concerning the project. This survey of users found that a smaller percentage of people attending the training sessions were using the program regularly than had been hoped for. However, most of those contacted felt that the program adequately served the needs of a pavement management system, and nearly all planned to use LVR more in the future. From the work done at The University of Texas and from suggestions from Forest Service users, several recommendations were made concerning future development for the program. Most important of these was the need for an organized data base to give the Forest Service controlled access to important information. This information is an extremely valuable tool for calibrating and improving the models to best suit Forest Service applications. Continued maintenance of LVR by making necessary improvements on a regular basis is naturally considered important in order to retain the integrity of the system.

From this study it is concluded that the immediate course of action recommended to the Forest Service is to expand the usage of the program on a national level. The system has been tested and is working. Modifications of certain models are in progress or are slated for the near future. The next step is for LVR users to become more acquainted with the most efficient and beneficial way to apply the program to their particular problems. The survey of users found that the ones who had used the program the most were the ones who like it the best. As the program is used more the applications become more apparent.

The Forest Service has an efficient pavement management system which will allow savings in manpower and cost and provide for optimal use of resources, provided that the LVR program is given sufficient use to determine its best applications, that a data base system is designed and used to calibrate and maintain the models in the future, and that present revisions of models and future developments continue.

NOTE TO PROSPECTIVE USERS

The LVR pavement management system program is presently operational, on a national basis, on the Forest Service Computer System. Forest Service personnel who are interested in using the LVR program should contact the Sponsor for this program in the Engineering Staff Unit of the Washington Office.

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APPENDIX A

SENSITIVITY ANALYSIS - FIGURES AND TABLES

TABLE 1. PAVED ROADS. AVERAGE LEVEL. RANKING, EXECUTION TIME, AND RESULTS OF VARIABLES HAVING THE MOST SIGNIFICANT EFFECT ON COST.

Sensitivity Analysis   Condition: Average   Type: Paved Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variable
All variables fixed at average level	25.9		117,474 107,327 105,238	1 Layer Design 2 Layer Design 3 Layer Design	
Traffic ADT logging trucks ADT Non-logging trucks Cum. 18-kip ESAL	26.7	216.5	L 82,266 H 170,499 L 72,764 H 156,071 L 73,090 H 152,587	88,232 83,307 79,497	1
Soil Support Subgrade	29.4	117.0	L 93,043 H 146,631 L 87,434 H 133,137 L 88,948 H 131,822	53,588 45,702 42,873	2
Regional Factor	22.0	44.7	L 105,359 H 136,110 L 96,979 H 125,364 L 95,369 H 123,819	30,751 28,384 28,449	3

(Continued)

TABLE 1. CONTINUED

Sensitivity Analysis   Condition: Average   Type: Paved Roads

Variable	Computer Execution Time (Seconds)		Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variable
	Low	High			
OVMIN	37.3	17.3	L 115,058	18,868	
			H 133,926		
			L 104,920	18,859	4
			H 123,779		
			L 102,875	19,412	
			H 122,287		
Salvage Value Top Layer	39.2	39.3	L 122,335	10,279	
			H 122,614		
			L 104,390	5,873	5
			H 110,264		
			L 102,301	5,873	
			H 108,175		
Annual Routine Maintenance Cost	25.8	25.9	L 114,292	7,422	
			H 121,714		
			L 104,144	7,422	6
			H 111,567		
			L 102,055	7,422	
			H 109,478		
Time Between Seal Coats	25.6	26.2	L 144,262	6,732	
			H 120,994		
			L 104,115	6,782	7
			H 110,897		
			L 102,006	5,677	
			H 107,683		

(Continued)

TABLE 1. CONTINUED

Sensitivity Analysis   Condition: Average   Type: Paved Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variable
Salvage Value of Second Layer	39.1	39.3	L 177,474 H 177,474 L 103,039 H 109,471 L 102,513 H 106,285	0 6,431 3,771	8
Material Cost, Layer Coefficient and Soil Support Second Layer	39.6	41.7	L 117,474 H 117,474 L 114,785 H 108,718 L 108,728 H 106,431	0 6,066 2,296	9
Terminal Serviceability Index, P2	23.3	38.3	L 114,505 H 120,222 L 104,357 H 109,820 L 103,940 H 107,767	5,717 5,462 3,826	10
Material Cost, Layer Coefficient and Soil Support Top Layer	23.0	91.0	L 118,276 H 119,165 L 110,282 H 104,929 L 105,446 H 103,779	888 5,353 1,667	11

(Continued)

TABLE 1. CONTINUED

Sensitivity Analysis Condition: Average Type: Paved Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variable
Swelling Clay Parameter	8.2	34.8	L 114,471 H 119,299	4,828	12
			L 104,323 H 109,151	4,828	
			L 103,545 H 108,025	4,480	
Non-deterioration Parameter P2P	22.8	40.4	L 114,529 H 119,275	4,745	13
			L 104,382 H 109,128	4,745	
			L 103,963 H 107,270	3,306	
Material Cost, Layer Coefficient and Soil Support Third Layer	36.0	41.5	L 117,474 H 117,474	0	14
			L 107,327 H 107,327	0	
			L 103,106 H 107,560	4,453	
Seal Coat Cost	26.0	25.9	L 116,138 H 119,478	3,340	15
			L 105,990 H 109,341	3,350	
			L 103,890 H 107,236	3,346	

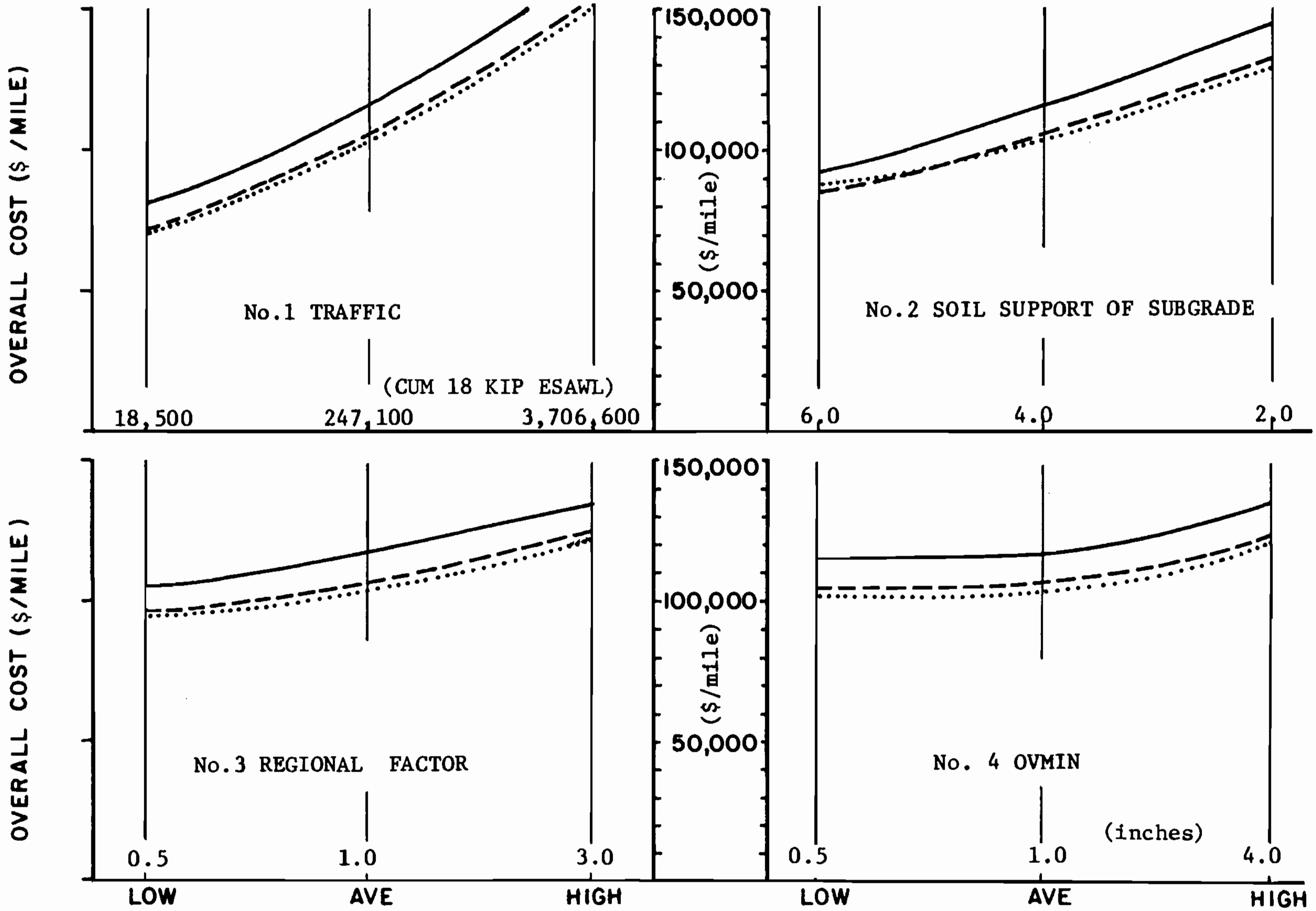

Fig 1. Effect of different variables at average level on total overall cost for paved roads.

One layer design
Two layer design
Three layer design

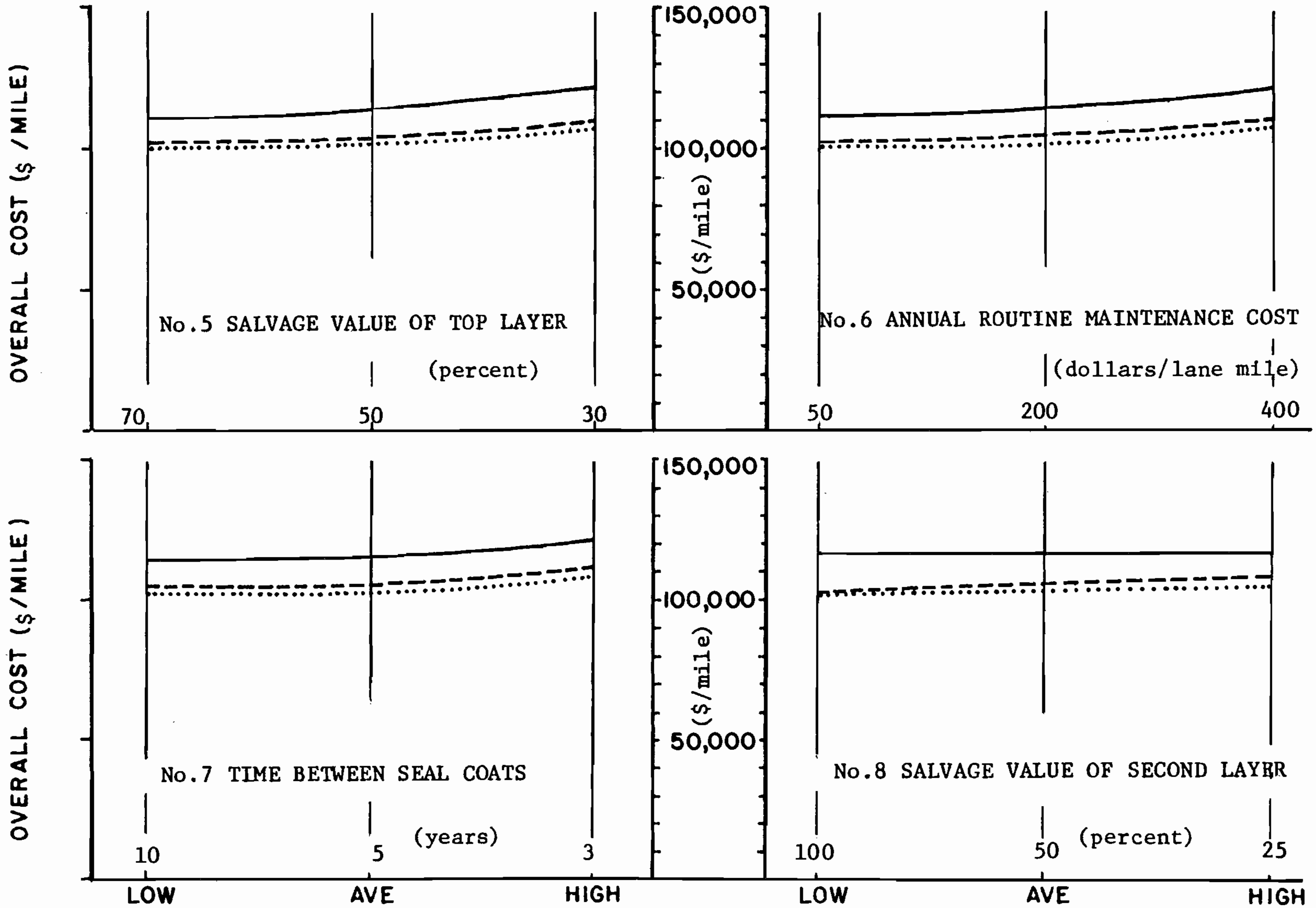

Fig 2. Effect of different variables at average level on total overall cost for paved roads.

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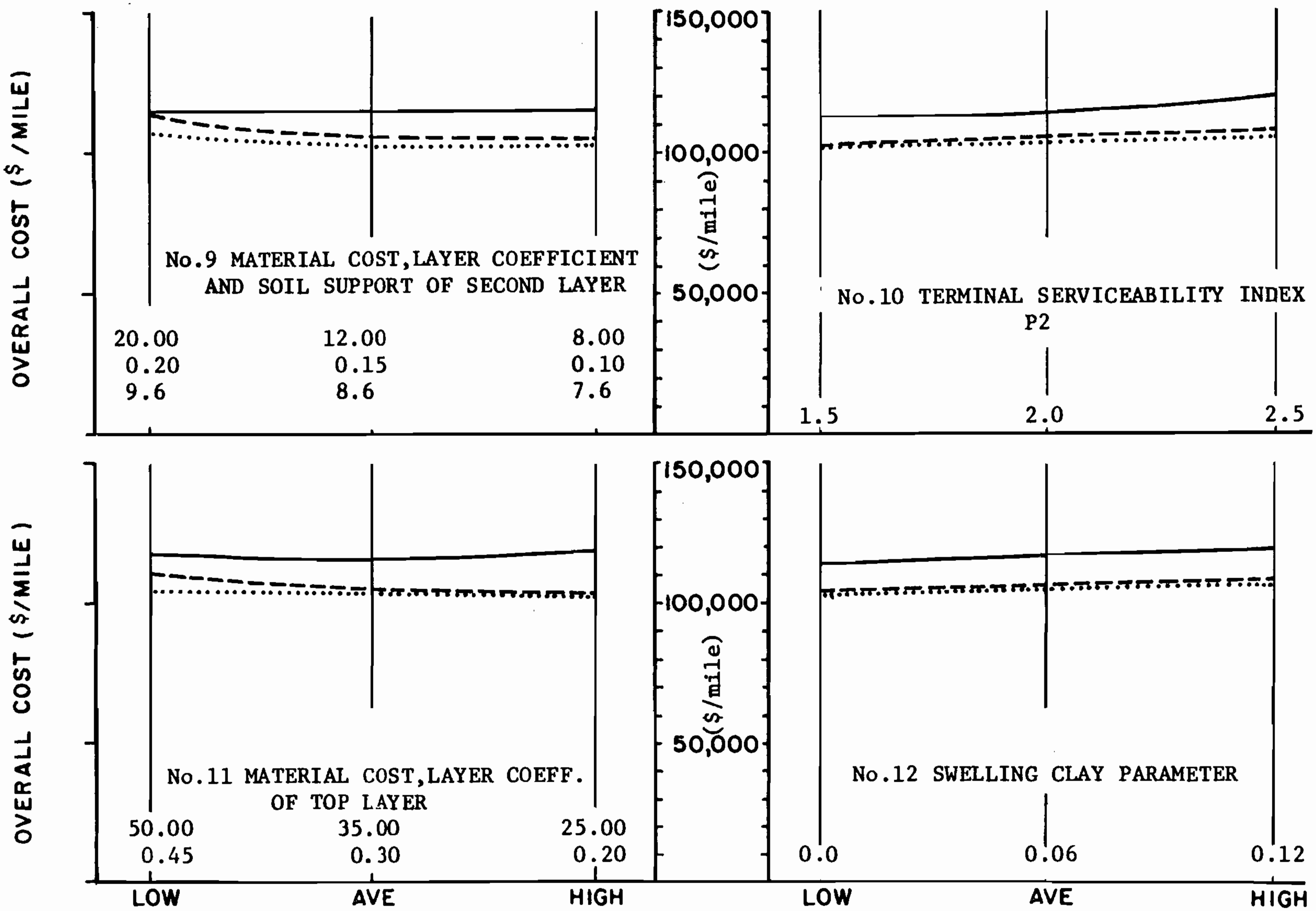

Fig 3. Effect of different variables at average level on total overall cost for paved roads.

——— One layer design
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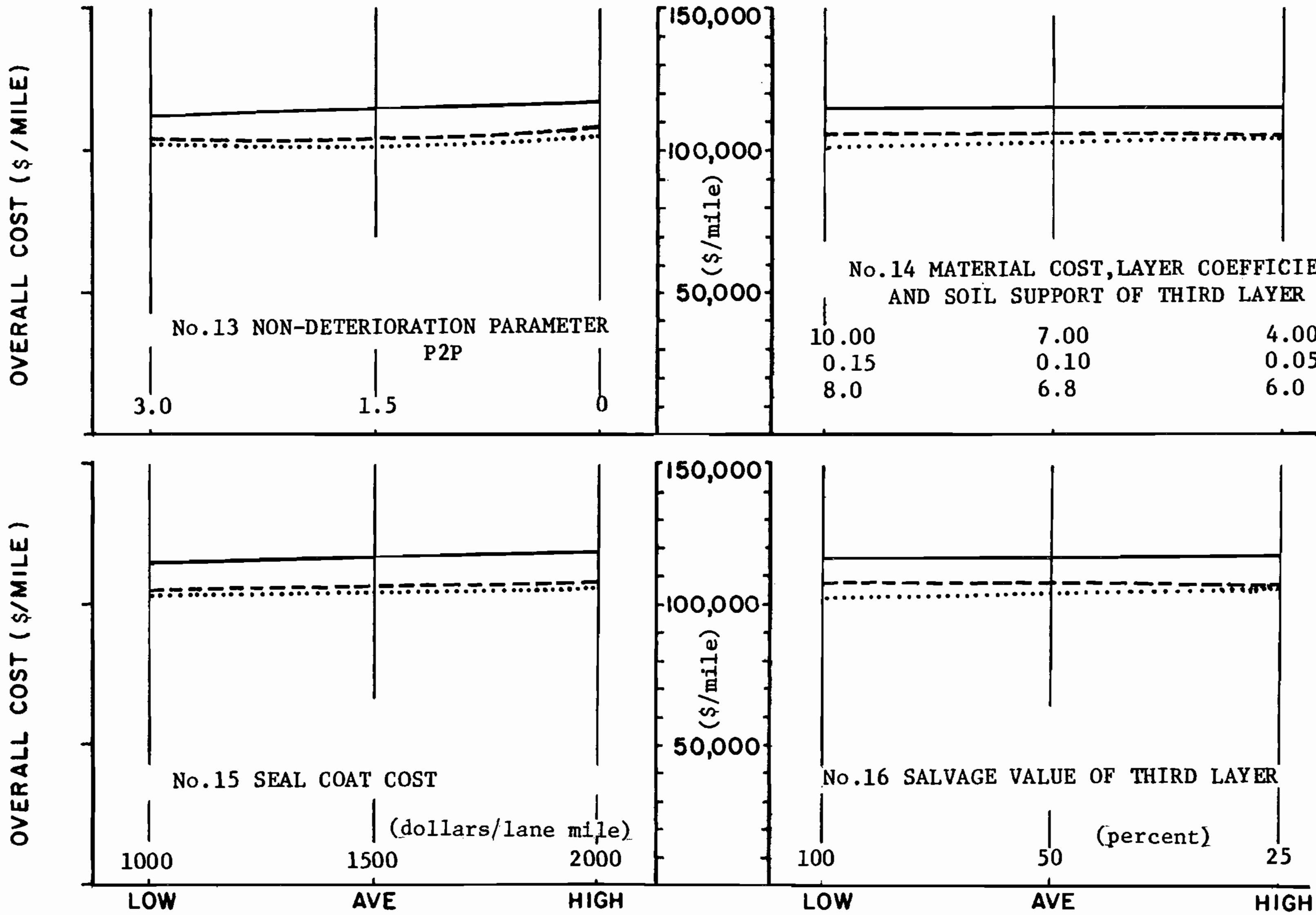

Fig 4. Effect of different variables at average level on total overall cost for paved roads.

———————— One layer design
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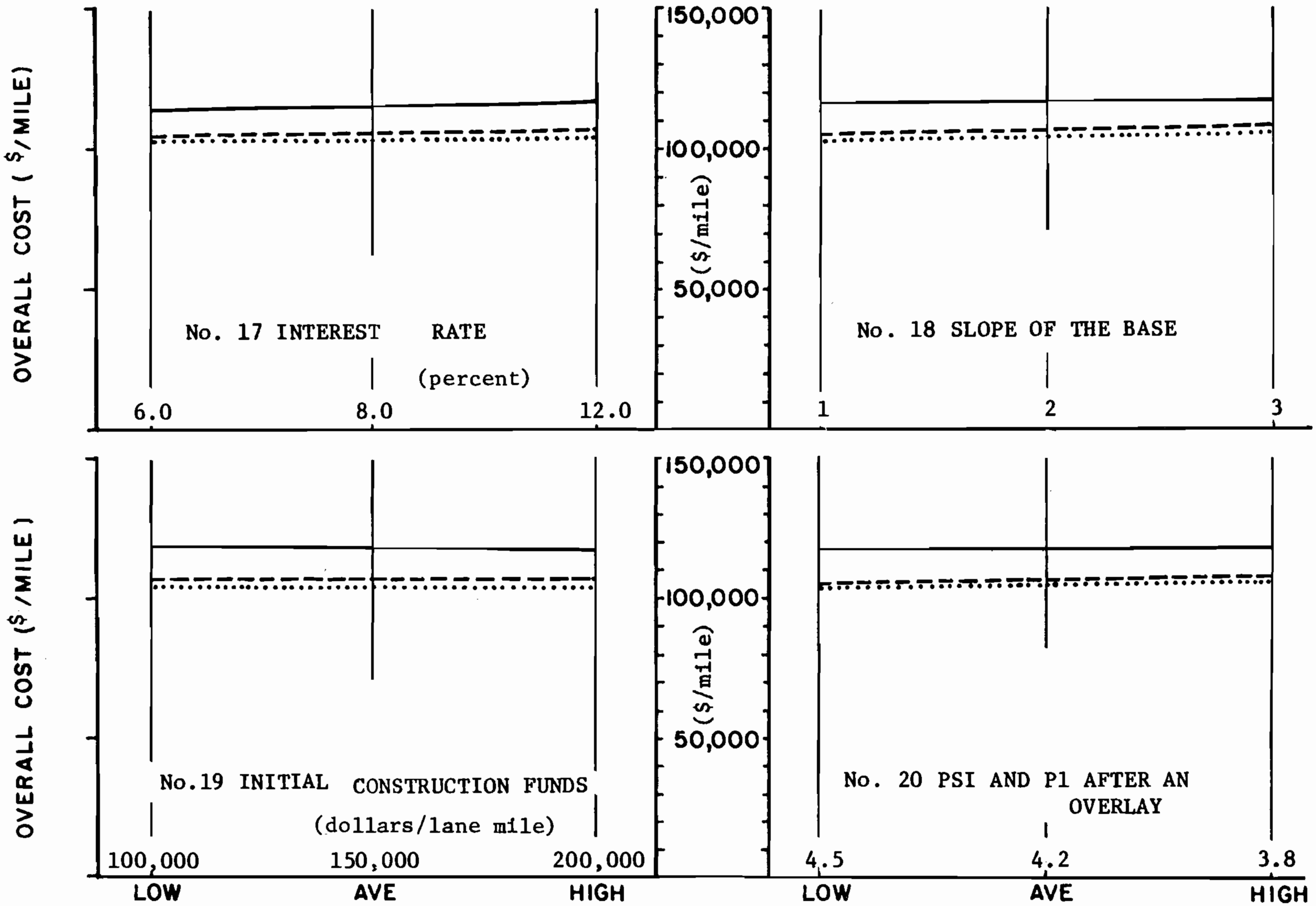

Fig 5. Effect of different variables at average level on total overall cost for paved roads.

One layer design
Two layer design
Three layer design

TABLE 2. PAVED ROADS. LOW LEVEL. RANKING, EXECUTION TIME, AND RESULTS OF VARIABLES HAVING THE LARGEST EFFECT ON COST.

Sensitivity Analysis — Condition: Low — Type: Paved Roads

Variable	Computer Execution Time (Seconds)		Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variables
	Average	High			
All variables fixed at low level	3.7		46,466 46,802 58,633	1 Layer Design 2 Layer Design 3 Layer Design	Note: Diff. is calculated Low vs. High Runs
Traffic: ADT non-logging trucks ADT logging trucks Cum. 18-kip ESAL	4.3	4.4	A 73,671 H 109,743 A 72,372 H 108,144 A 76,770 H 107,264	63,277 61,341 48,630	1
Soil Support of Subgrade	3.9	4.5	A 58,633 H 72,204 A 62,381 H 81,360 A 63,980 H 83,486	25,737 34,558 24,852	2
Regional Factor	3.9	4.5	A 54,912 H 64,603 A 53,976 H 63,914 A 63,167 H 72,236	18,136 17,112 13,602	3

(Continued)

TABLE 2. CONTINUED

Sensitivity Analysis   Condition: Low   Type: Paved Roads

Variable	Computer Execution Time (Seconds) Average	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variable
Interest Rate	3.7	3.7	A 42,799 H 39,483 A 42,185 H 38,038 A 52,553 H 47,122	6,983 8,763 11,511	4
Material Cost, Layer Coefficient and Soil Support Third Layer	-- This information not printed in output	--	A 46,466 H 46,466 A 46,802 H 46,802 A 55,084 H 51,534	0 0 7,098	5
Annual Routine Maintenance Cost	3.7	3.7	A 48,976 H 52,322 A 49,311 H 52,658 A 61,143 H 64,489	5,856 5,856 5,856	6
Time Between Seal Coats	3.9	4.1	A 47,967 H 50,119 A 48,302 H 50,455 A 60,134 H 62,286	3,652 3,652 3,652	7

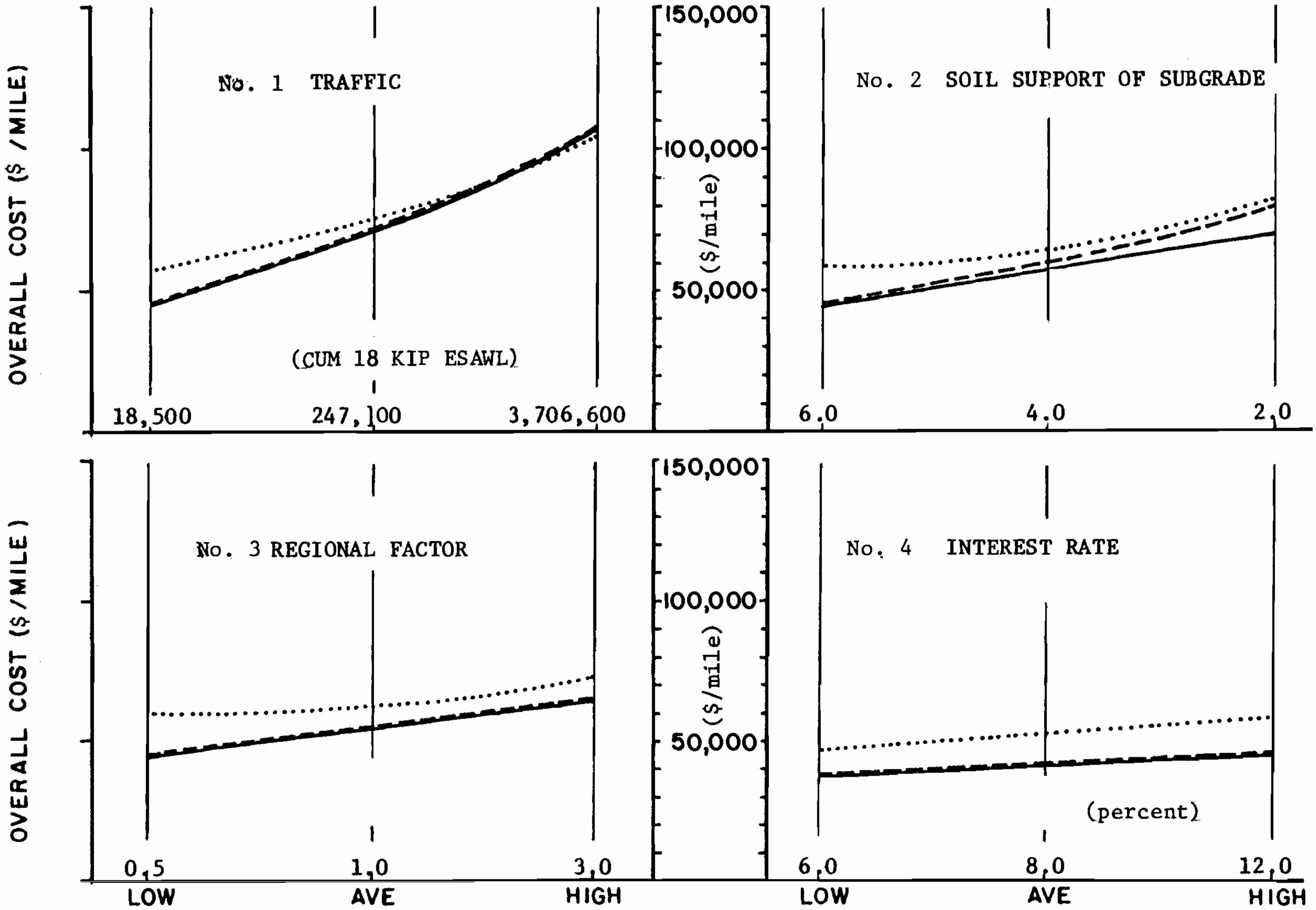

Fig 6. Effect of different variables at low level on total overall cost for paved roads.

One layer design
Two layer design
Three layer design

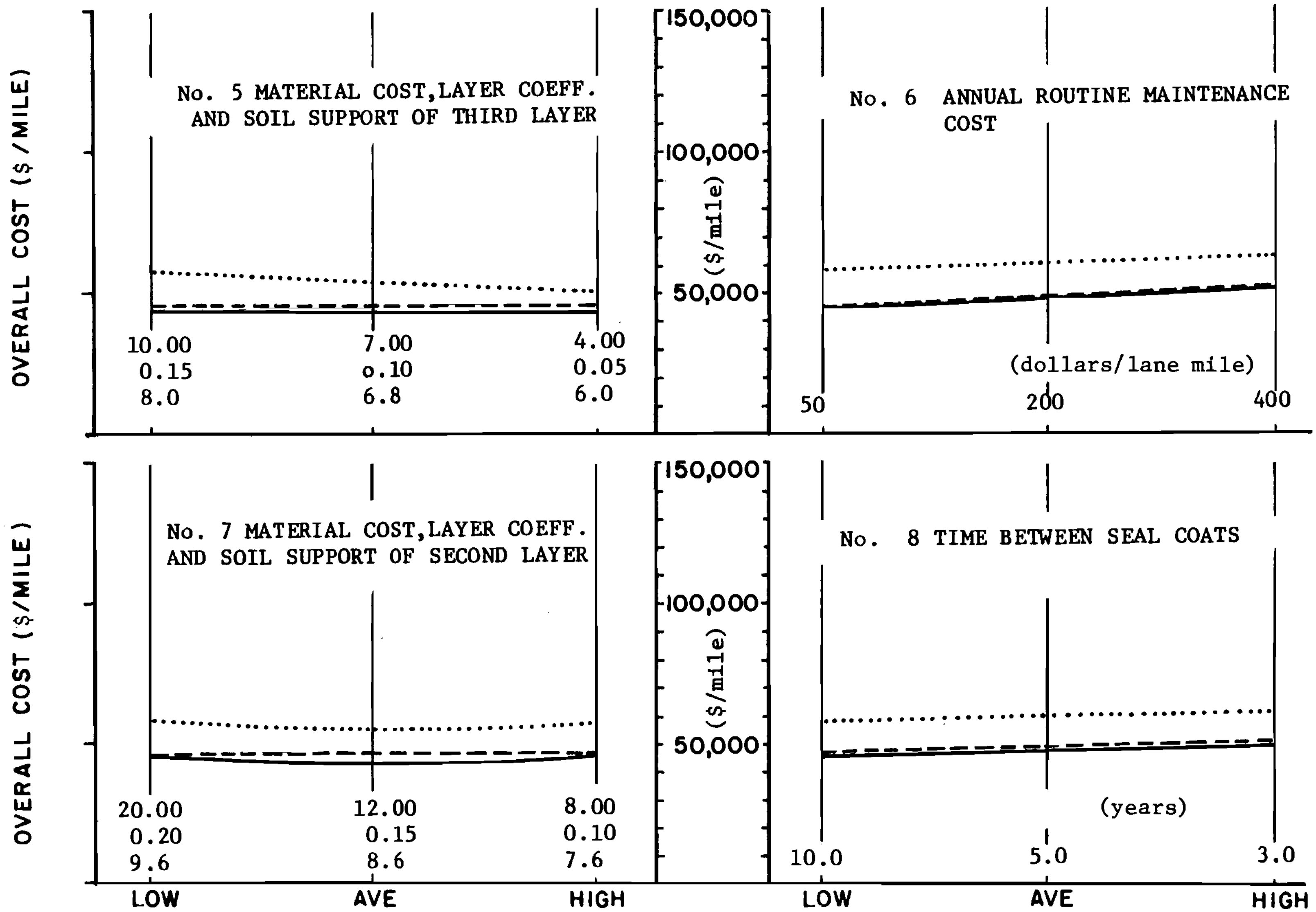

Fig 7. Effect of different variables at low level on total overall cost for paved roads.

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.... Three layer design

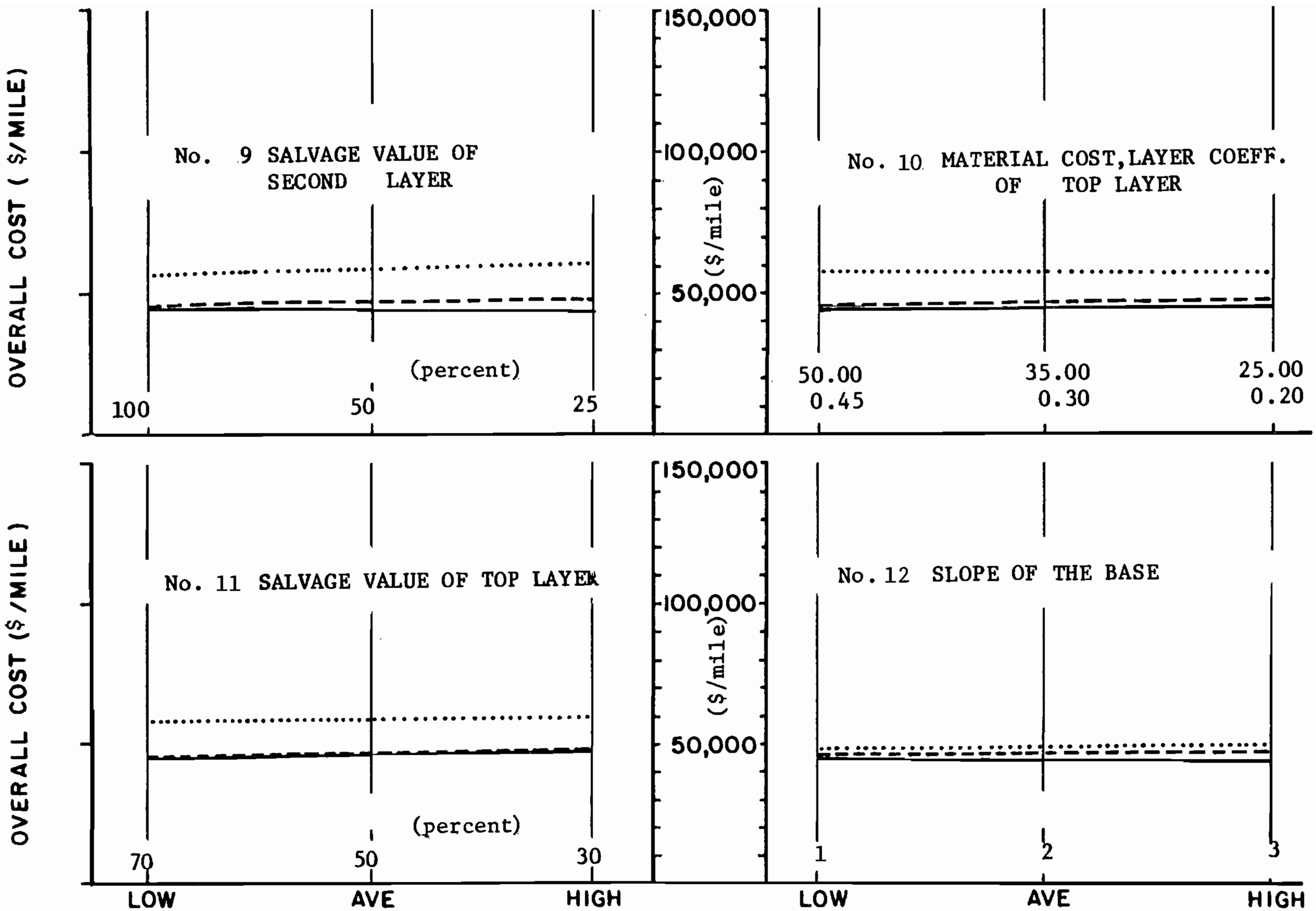

Fig 8. Effect of different variables at low level on total overall cost for paved roads.

———————— One layer design

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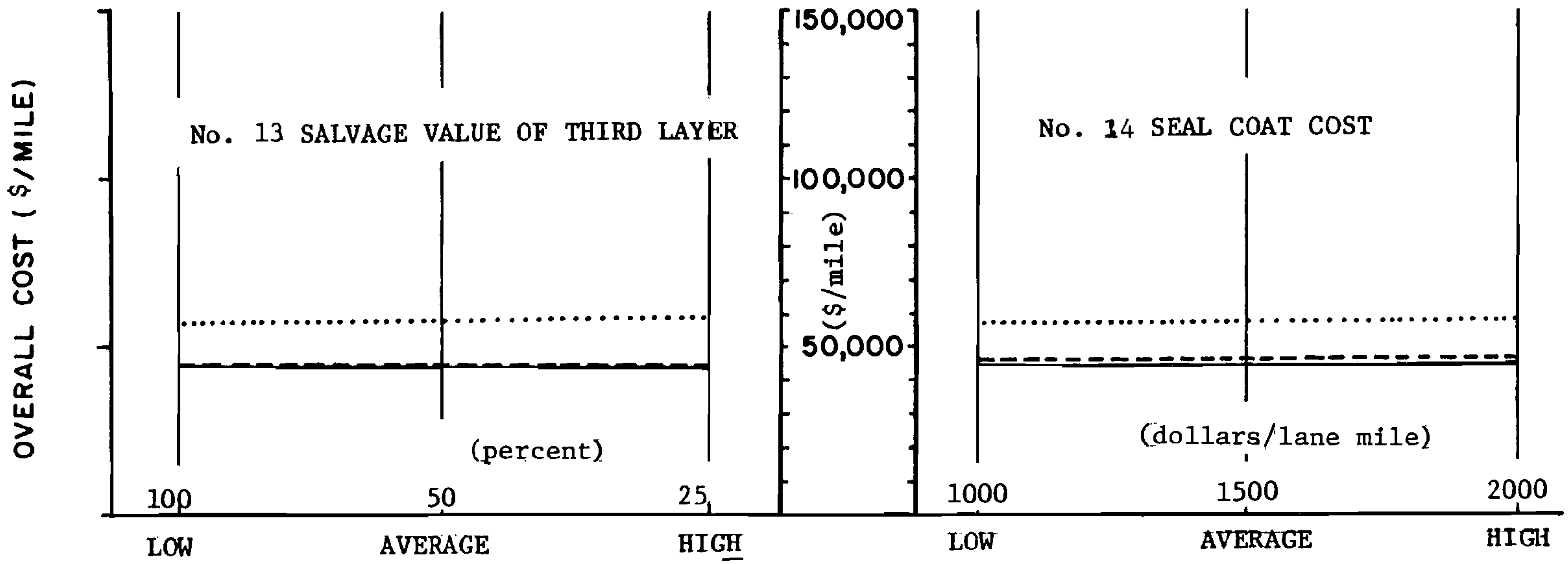


Fig 9. Effect of different variables at low level on total overall cost for paved roads.

———————— One layer design
- - - - - - - - - Two layer design
.... Three layer design

TABLE 3. AGGREGATE SURFACED ROADS. AVERAGE LEVEL. RANKING, EXECUTION TIME, AND RESULTS OF VARIABLES HAVING THE MOST SIGNIFICANT EFFECT ON COST

Sensitivity Analysis   Condition: Average   Type: Aggregate Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variables
All variables fixed at average level	21.8		125,102 123,202	1 Layer Design 2 Layer Design	
Traffic ADT non-logging trucks ADT logging trucks Cum. 18-kip ESAL	2.1	2.1	L 61,489 H * L * H * * too restrictive	63,612 Compared with average	1
Material Cost, Layer Coefficient and Soil Support Top Layer	15.2	30.2	L 167,771 H * L 175,936 H 110,359 * too restrictive	65,577	2
Aggregate Surface Loss (in/MBF)	4.6	2.2	L 94,606 H * L 91,331 H * * too restrictive	30,495 31,871 Compared with average	3

(Continued)

TABLE 3. CONTINUED

Sensitivity Analysis   Condition: Average   Type: Aggregate Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variables
Soil Support Value of Subgrade	32.2	17.7	L 91,348 H * L 121,786 H 147,288 * too restrictive	25,519	4
Salvage Value of Top Layer	21.9	21.9	L 110,951 H 132,176 L 110,210 H 129,698	21,224 19,488	5
OVMIN	4.9	236.3	L 120,907 H 133,710 L 119,810 H 131,427	12,803 11,616	6
Grading Cost	21.9	21.9	L 121,275 H 132,755 L 119,298 H 131,010	11,479 11,712	7
Regional Factor	24.1	18.4	L 114,611 H * L 121,768 H 130,978 * too restrictive	9,209	8

(Continued)

TABLE 3. CONTINUED

Sensitivity Analysis Condition: Average Type: Aggregate Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variables
Material Cost, Layer Coefficient and Soil Support Second Layer	41.0	16.5	L 125,102 H 125,102 L 134,805 H 126,338	0 8,467	9
Swelling Clay Parameter	15.1	21.9	L 117,935 H 125,127 L 121,768 H 123,399	7,191 1,630	10
Interest Rate	21.9	21.9	L 118,674 H 125,861 L 117,626 H 123,410	7,186 5,784	11
XTTO Minimum Length of Performance Period	32.9	4.9	L 123,301 H 124,082 L 122,214 H 129,414	781 7,199	12
Slope of The Base	21.8	21.5	L 122,350 H 127,853 L 119,725 H 126,678	5,502 6,953	13

(Continued)

TABLE 3. CONTINUED

Sensitivity Analysis Condition: Average Type: Aggregate Roads

Variable	Computer Execution Time (Seconds) Low	High	Overall Cost ($ per Mile)	Difference ($ per Mile)	Ranking of Variables
OVMAX all Rehabilitations	12.0	22.3	L --- H 124,928 L 130,055 H 123,202	6,852	14
Time Between Gradings	20.5	24.4	L 123,358 H 129,036 L 121,290 H 127,121	5,677 5,831	15
Annual Routine Maintenance Cost	21.9	21.9	L 124,041 H 127,222 L 122,142 H 125,323	3,181 3,181	16

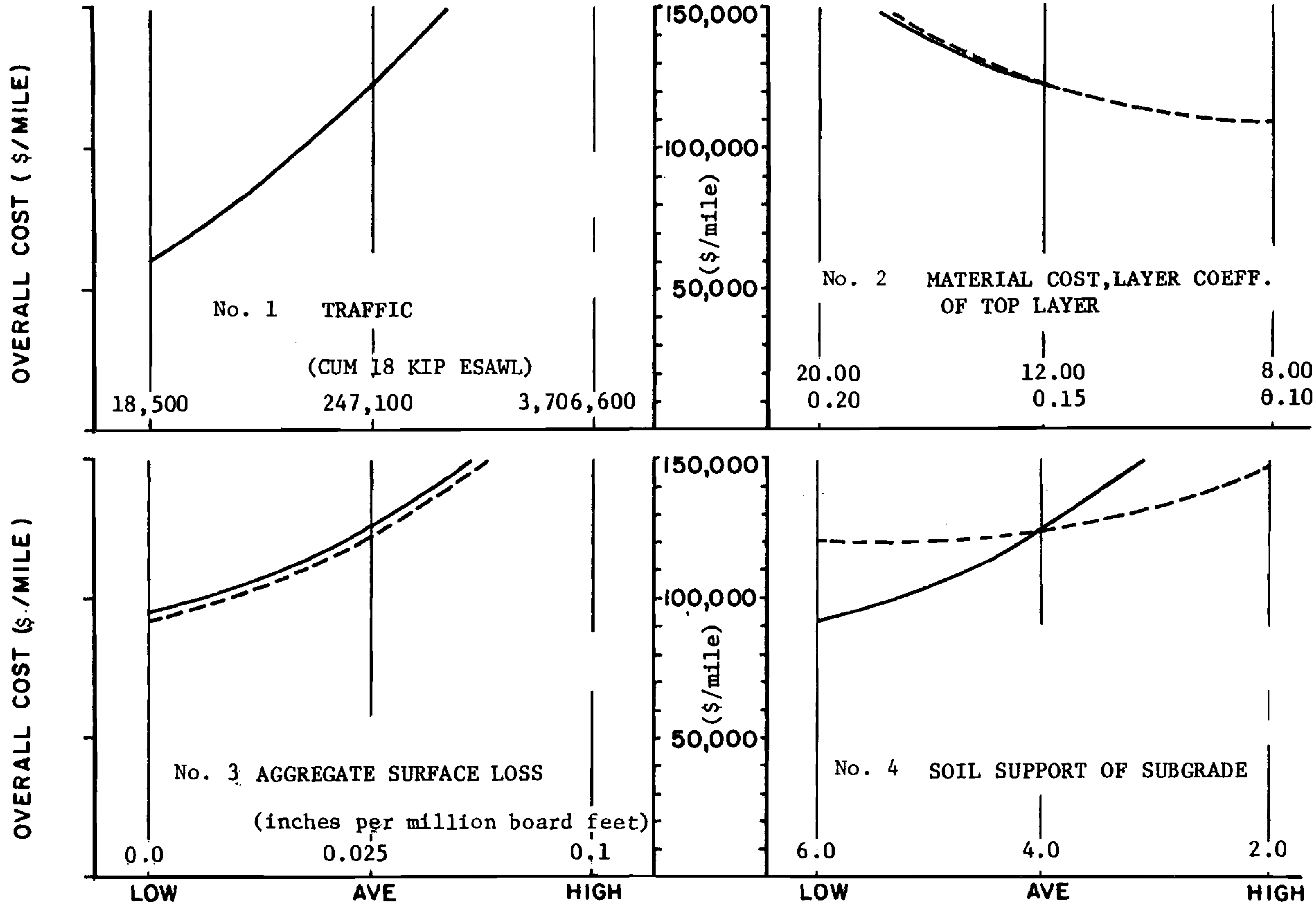


Fig 10. Effect of different variables at average level on total overall cost for aggretate surfaced roads.

———————— One layer design
- - - - - - - - - - Two layer design
.... Three layer design

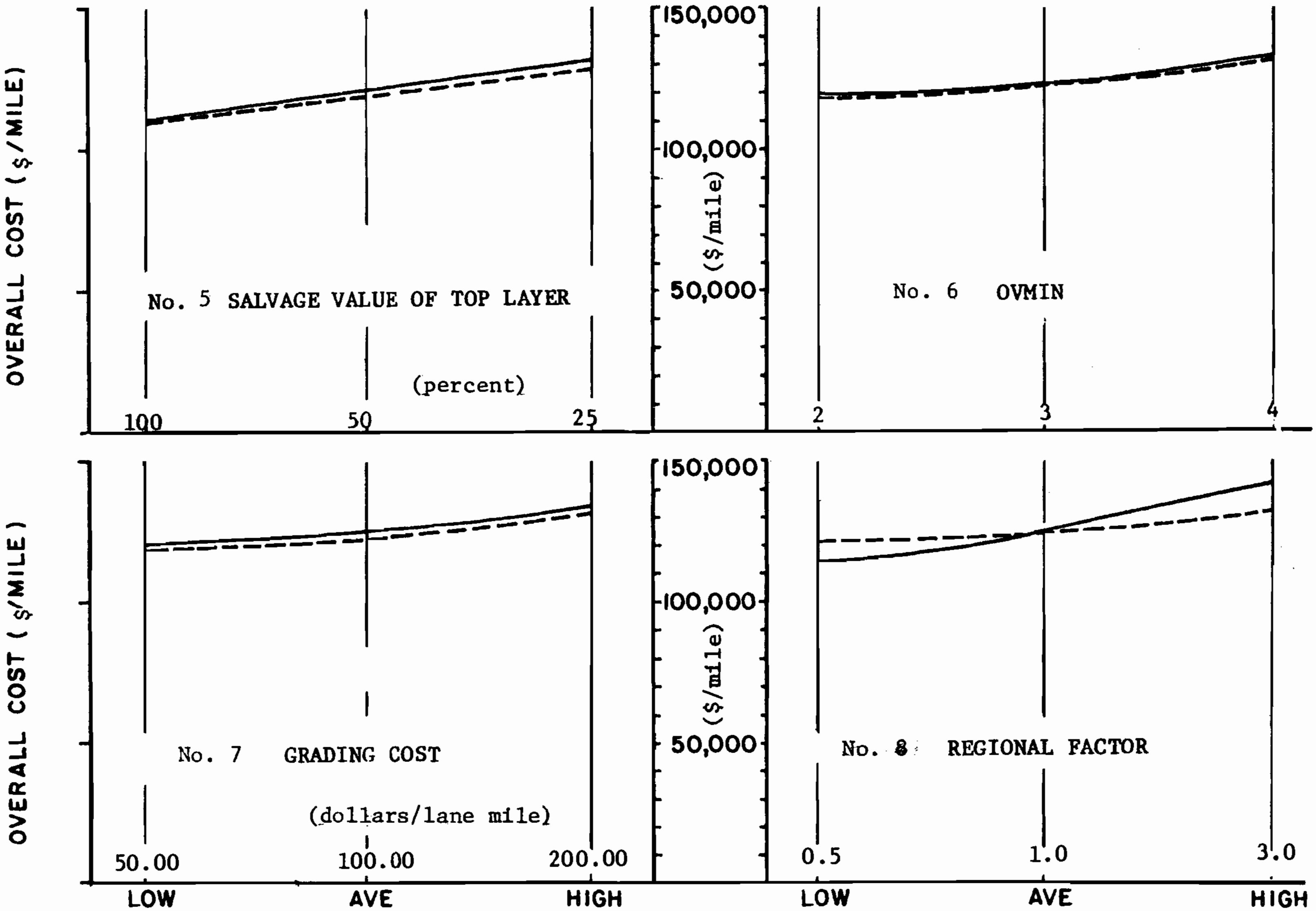


Fig 11. Effect of different variables at average level on total overall cost for aggregate surfaced roads.

One layer design
Two layer design
Three layer design

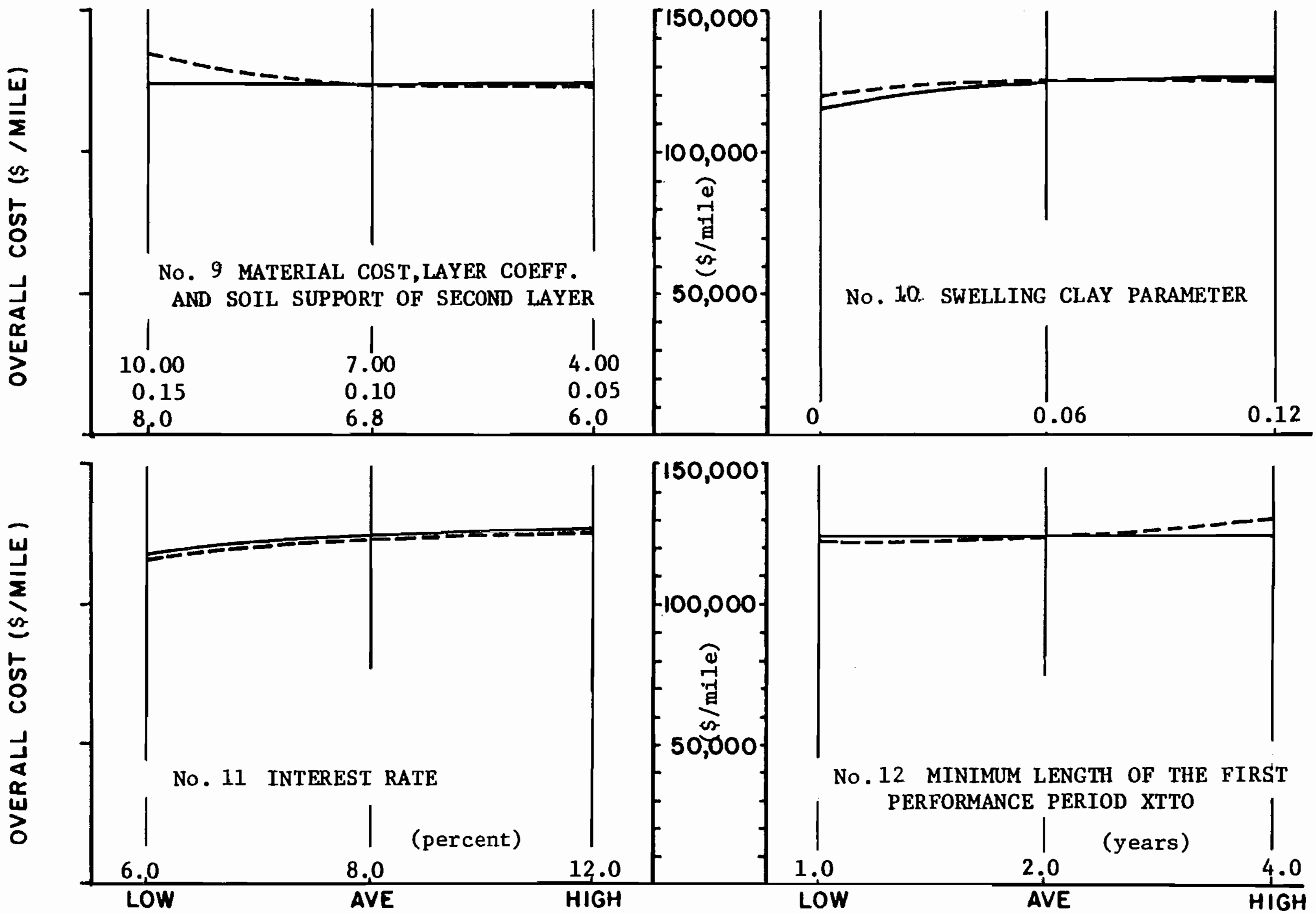


Fig 12. Effect of different variables at average level on total overall cost for aggregate surfaced roads.

———————— One layer design
- - - - - - - - - Two layer design
.... Three layer design

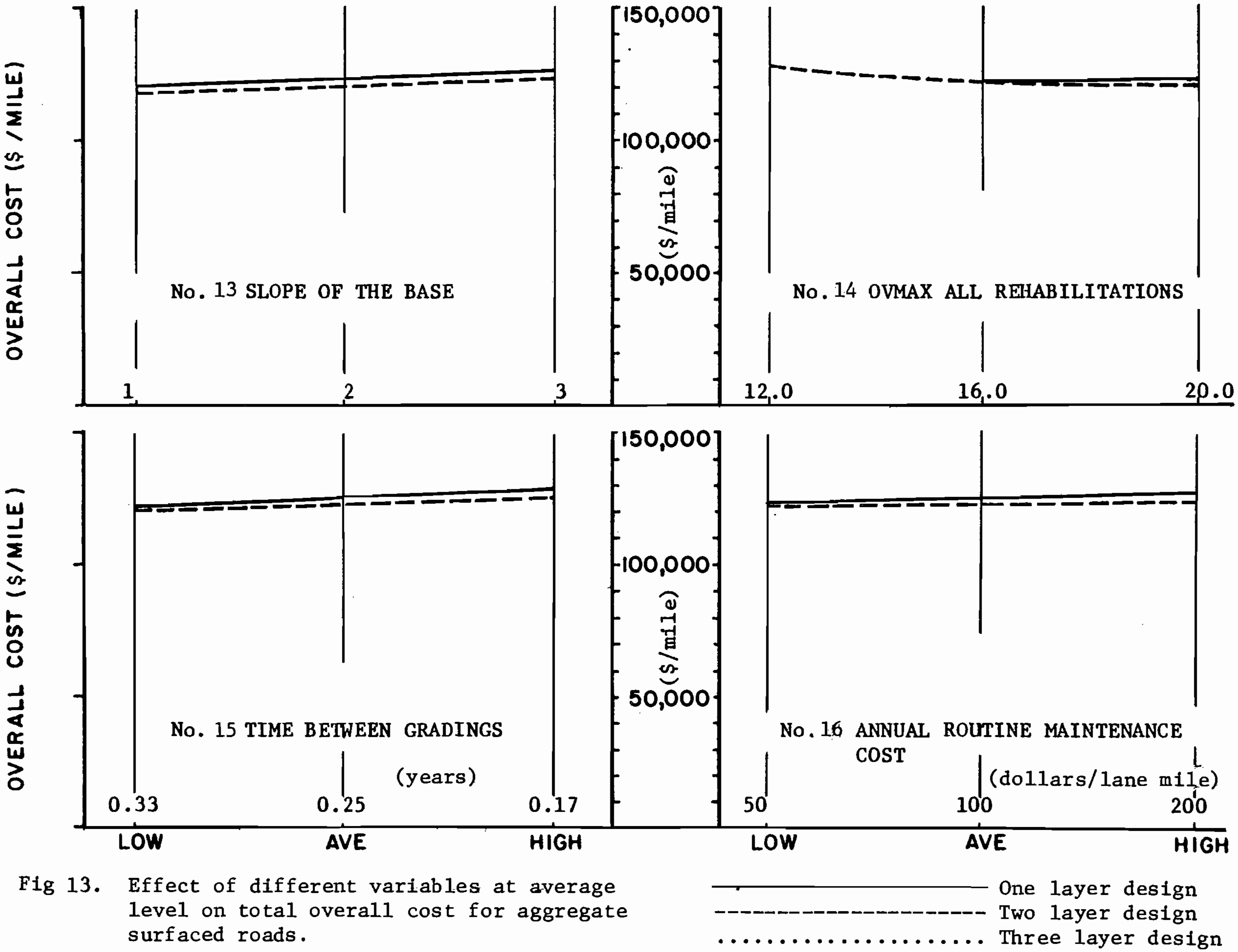


Fig 13. Effect of different variables at average level on total overall cost for aggregate surfaced roads.

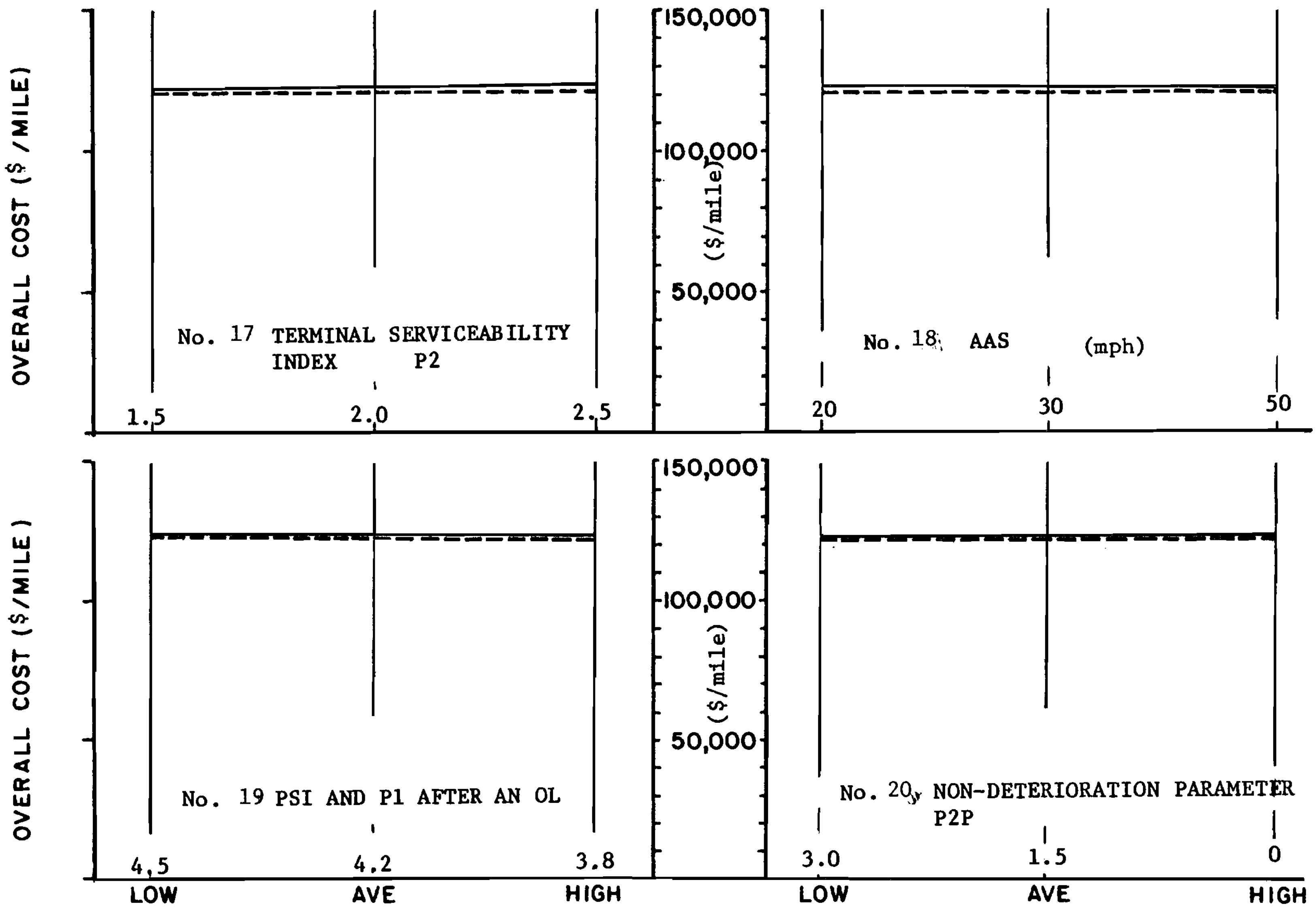


Fig 14. Effect of different variables at average level on total overall cost for aggregate surfaced roads.

———— One layer design
- - - - Two layer design
.... Three layer design

APPENDIX B

PHASE III WORK PLAN OUTLINE

PAVEMENT MANAGEMENT SYSTEM FOR FOREST SERVICE ROADS
PHASE III - WORK PLAN OUTLINE
Forest Service Agreement No. 13-883

OBJECTIVE

The objective of Phase III is to implement the LVR program within the Forest Service so that pavement design and management will be done in an optimal, systematic way. It is proposed that this objective can be realized by performing the following tasks:

(1) conduct a sensitivity analysis,
(2) investigate RDS interaction,
(3) conduct a trial usage of the LVR program,
(4) plan program revisions,
(5) prepare user's manual,
(6) estimate vehicle operating cost, and
(7) extend the trial usage.

In order to complete these tasks, a time schedule has been formulated for a 24 month period as shown in Fig 1. The following paragraphs explain each of the work items in more detail.

CONDUCT A SENSITIVITY ANALYSIS

One of the first tasks should be to perform sensitivity analyses on the LVR computer program. The basic concept of this task is to evaluate the effect of changes in the magnitude of each variable on the total project cost and rehabilitation strategy. Thus, the relative effects of the different input variables can be compared. This could provide the following guidelines for future users:

(1) The variables having only a small effect on the final answer could fixed at a mean value; thus, reducing the total number of input variables that must be developed by the user.

(2) Provide guidance to the user in budgeting resources for characterizing the various input variables. Obviously, more time should be spent on the most sensitive variables. Without this type of guidance, there may be a tendency to spend excessive resources in characterizing variables that have very little effect on the final answer.

(3) Identify opportunities for future studies. Obviously, the most sensitive variables that have the least reliable information should be given priority in future studies.

The sensitivity analyses would be performed in two phases. The first phase could be a simple sensitivity analysis, where a realistic range and average value for each of the variables would be selected. For the simple sensitivity analysis, one of the variables would be selected and solutions run at the low value and high value with all the other variables fixed at the average value. Solutions would be made for the next variable in the same manner.

The second phase of the sensitivity analysis would be a more complex factorial analysis using sound statistical techniques. Rather than run a 2^n factorial for the large number of variables which would permit an analysis of all main effects and all interactions, a reduced experiment would permit an analysis of main effects and first order interactions and also conserve both time and computer costs. Some of the variables that have either a minimal total effect on the solution or the interactions with other variables are probably not significant could be lumped together in groups. Variables that may fall into group categories are:

(1) user delay variables,
(2) performance variables,
(3) non-traffic deterioration variables,
(4) thickness constraints,
(5) cost constraints,
(6) constraints on length of performance periods,
(7) cost per compacted cubic yard for different materials, and
(8) traffic history variables.

In the sensitivity analysis all variables in a group will be varied simultaneously in order to determine their maximum combined effect under reasonable circumstances. If one set of group variables proves to be important, then the variables in the indicated group will be investigated individually. In addition, the maximum effects of the interactions of these variables in a given category will be investigated in order to produce a maximum effect. A fractional factorial experimental design would be employed to estimate main effects and first order interactions. The activities under this task are contained in Fig 1 between nodes 2-3-9-22-24-33-37, during the period from October 1, 1976 to November 30, 1977.

INTERACTION WITH ROAD DESIGN SYSTEM (RDS)

An important consideration for extensive use of the LVR computer program is that it effectively interact with the RDS system developed by the Forest Service. Proper interaction between the present components of RDS and the LVR program could be accomplished by:

(1) Determining the entry points at which pavement design should be considered before making earthwork quantity calculations. This would permit accurate total cost predictions to be made since thicker pavement sections would require more material removal for side slopes and cuts on side hill sections. In addition, more accurate estimates could be made of such items as acreage exposed for revegetation, lengths of culverts, amount of land removed from timber production, etc.

(2) Determining the effect of the use of pavement design program on overall running efficiency of the RDS - LVR combination system.

(3) Developing a strategy for selecting or incorporating different pavement thickness designs into a given trial highway geometric alignment.

The activities under this task are contained in Fig 1 between nodes 16-20-29-32-38 during the period June 3, 1977 to May 1, 1978.

CONDUCT TRIAL USAGE OF LVR

Prior to an extensive use of the LVR program by the Forest Service, a trial usage could be made of the program in order to solve practical problems that will develop when engineers in the field begin to use the program. In this way, any irrationalities or programming errors would be discovered and corrected. It is essential during this phase that the Forest Service Staff selected be fully cooperative and feel that the system would be of value to them, if implemented in their Region. Following are the general work items proposed for this task:

(1) select Regions for trial usage; tentative selections are Regions 6 and 8,

(2) meet with personnel from selected regions to plan training requirements, Fig 1 nodes 7-14,

(3) trial Regional personnel who will use programs, Fig 1 nodes 14-15 and 18-19,

(4) survey users to determine desirable modifications to the program, bugs that have been found, or alterations in user's manual to make explanations clearer, Fig 1 nodes 15-18, 15-25-28, and 19-25-28,

(5) report results of trial usage and survey in the form of a Technical Memorandum, Fig 1 nodes 28-31.

PLAN PROGRAM REVISIONS

The following work tasks were discussed as desirable computer program revisions and additions during a meeting of the Forest Service Advisory Committee at Fort Collins, Colorado during May 25-27, 1976:

(1) Develop a printer-plot option for the PSI curve for the optimum design.

(2) Include a deflection design method along with the present AASHTO and modified Corps of Engineers (2-inch rut depth) equations presently in the program. This work item is included in Fig 1 under nodes 2-5-11-17. Notice that the implementation of the deflection design procedure is scheduled for completion before the first training session.

(3) Include an operating cost versus PSI curve in order to reflect more accurately the operating cost as affected by the overlay or gravel addition strategies considered in all candidate designs. This item can be accomplished if the data are developed independently of this study since substantial effort will be required.

PREPARE USER'S MANUAL

Continue inclusion of information into the User's Manual as experience in the trial usage regions indicates. The object is to provide to the user a document that will be self-sufficient in providing all tables, charts and written documentation necessary for selection of input values for all variables required to run the program. The form of the User's Manual will follow that of Chapter 50 of the Forest Service Handbook System.

Development of the User's Manual will reflect all information collected from a survey of users to determine modifications or clarifications in the manual that will enhance the usability of the program. In addition, comments that are received during the period of extended usage will be considered for inclusion in the final version of the User's Manual. This activity forms one of the continuous threads extending throughout the length of the project, as illustrated by Fig 1, nodes 2-6-12-23-27-35-38-40-42.

ESTIMATE VEHICLE OPERATING COST

Coordination with the University of California at Berkeley should continue in an attempt to utilize information developed for estimating vehicle operating cost. When a usage program is developed and available, input statements are available in LVR for use of these costs in making more rational choices between paved and unpaved designs for a given alignment. Working programs have been developed at the University of California and a preliminary version of the program is operational on the University of Texas computer. However, neither of the models used in the program nor the output have been finalized by the University of California therefore the results obtained from them must be used cautiously.

EXTEND THE TRIAL USAGE

After the user's manual has been developed, information has been obtained from the initial trial usage and problems with bugs have been minimized, the trial usage of the system could be extended. It is anticipated that two additional regions could be reached through one additional training session and trial usage. These regions should be selected based on interest expressed by other regions that were not included in the initial trial usage. Training sessions should be conducted to familiarize the users with the program and could possibly be coordinated with other training scheduled by the Regions. This activity is included in Fig 1 between nodes 30-36-39-41.

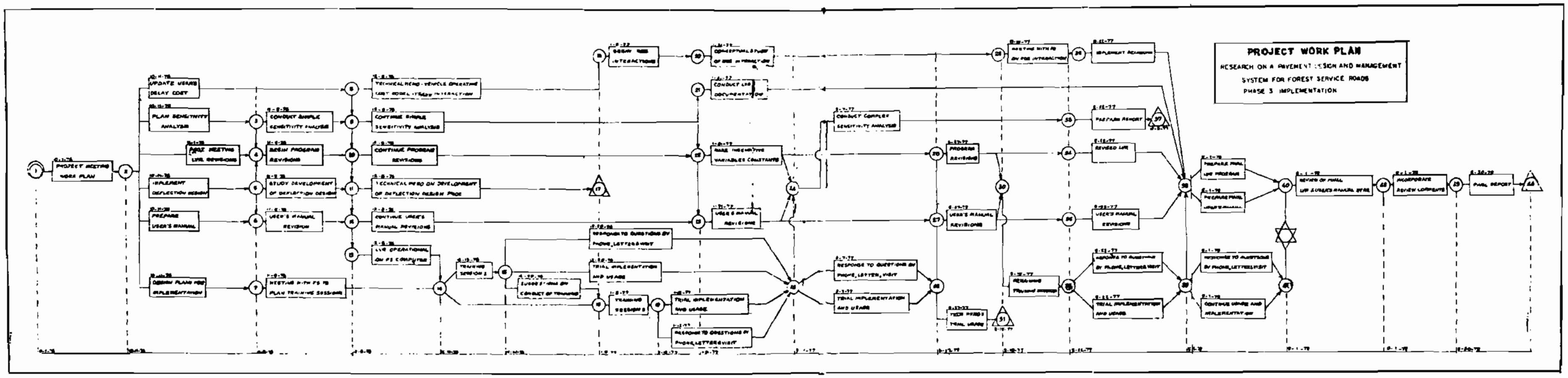


Fig 1. Project flow plan work diagram - Phase III.

APPENDIX C

LIST OF TRAINING SESSIONS AND ATTENDEES

AND TYPICAL AGENDA

ATTENDEES AT TRAINING SESSION NO. 1
Portland, Oregon (Region 6)
December 20-21, 1976

Name	Forest or Regional Office
Jim Adams	Wallawa-Whitman National Forest
Roy Arnoldt	Umpqua National Forest
Cal Blackburn	Wenatchee National Forest
Ronald Burgman	Malheur National Forest
Bruce Carr	Colville National Forest
D. Erwin	Olympic National Forest
D. Greenway	Siskiyou National Forest
Dave Haddock	Gifford Pinchot National Forest
Robert Haye	Umatilla National Forest
Dennis Larson	Olympic National Forest
Bob Mitchell	Regional Office
John Mohney	Regional Office
Vern Newton	Umpqua National Office
Don Smith	Gifford Pinchot National Forest
Everett Swayne	Malheur National Forest
Bruce Vandre	Siskiyou National Forest
Ron Weber	Colville National Forest
Ron Williamson	Regional Office
Bob Young	Siuslaw National Forest

ATTENDEES AT TRAINING SESSION NO. 2

Atlanta, Georgia (Region 8)

March 30-31, 1977

Name	Forest or Regional Office
James Boyd	Daniel Boone National Forest
Dennis Bradford	National Forest of Alabama
Jack Callahan	National Forest of Texas
Steve Comeaux	Ozark & St. Francis National Forest
Dave Franklin	Regional Office 8
Kerry Odle	National Forest of Mississippi
Wayne Orr	National Forest of North Carolina
Ronnie Raum	National Forest of North Carolina
Charles E. Rozier	Jefferson National Forest
Mack Waller	Kisatehie National Forest

ATTENDEES AT TRAINING SESSION NO. 3
Portland, Oregon (Region 6)
September 7 - 9, 1977

Name	Forest or Regional Office
Jerry McConnell	Mt. Hood National Forest
Paul Enburg	Regional Office
Bill Martin	Deschutes National Forest
Ed Farr	Umpqua National Forest
Vern Newton	Umpqua National Forest
Roy Arnoldt	Umpqua National Forest
Don Duncan	Deschutes National Forest
Charlie Zeits	Mt. Hood National Forest
Ross Ten Eyck	Mt. Hood National Forest
Fred Brovold	Mt. Hood National Forest
Ernie Disbrow	Mt. Hood National Forest
Gordon Rutter	Umpqua National Forest
John Nakads	Deschute National Forest
Jim Johnson	Umpqua National Forest
John Mohney	Regional Office
Bob Parker	Deschutes National Forest
Tom Shuman	Deschutes National Forest
Ron Torgeman	Deschutes National Forest
Doug Rieper	Mt. Hood National Forest
Dave Nordengren	Regional Office

ATTENDEES AT TRAINING SESSION NO. 4

Missoula, Montana

October 3-4, 1977

Name	Forest or Regional Office
Gerald Knapp	Clearwater National Forest (R-1)
Jon Dunlop	Clearwater National Forest (R-1)
Rich Kennedy	Kootenai National Forest (R-1)
Mike Mitchell	Lolo National Forest (R-1)
Lee Collett	Kootenai National Forest (R-1)
Gary Shulze	Superior National Forest (R-9)
Bob Harmon	Monongahela National Forest (R-9)
John O'Reilly	Nezperce National Forest (R-1)
Don Bennett	Idaho Panhandle National Forest (R-1)
Jim Northrup	Idaho Panhandle National Forest (R-1)
Joe Knudsen	Regional Office 1
Dick Creed	Gallatin National Forest (R-1)
Bill Cramer	Regional Office 1
Jon Achoff	Regional Office 1
Gary W. Moats	Medicine Bow National Forest (R-2)
Lee Landman	Regional Office 1
Glade Roberts	Regional Office 1
Duane Logan	Regional Office 3
John Warning	Burlington N.
Fred Dalbec	Nezperce National Forest (R-1)
Martin Everitt	Regional Office 2
Eugene D. Hansen	Regional Office 4
Bob Hinshaw	Regional Office 1

TYPICAL AGENDA FOR IMPLEMENTATION OF PAVEMENT MANAGEMENT SYSTEM WORKSHOP

Day and Time	Subject	Leader
Monday		
1:00 - 5:00 p.m.	Review of Chapter 50 Design Method	Hinshaw & Monlux
Tuesday		
7:30 - 9:30 a.m.	Overview of System. Inputs, Variables Considered, and Output.	Dr. Frank McCullough
9:30 - 11:30	Use of System. Detailed User Guide, Demonstration of Sample Problems.	Dr. Frank McCullough Dr. Freddie Roberts
11:30 - 12:30	Lunch	
12:30 - 4:30 p.m.	Use of System (Continued)	
Wednesday		
7:30 a.m. - 4:30 p.m.	Use of System (Continued)	
Thursday		
7:30 a.m. - 4:30 p.m.	Optional Workshop. Attendees should bring problems from Forests to work on.	Dr. Freddie Roberts

APPENDIX D

USER QUESTIONNAIRE

LVR QUESTIONNAIRE FOR FOREST SERVICE USERS

Name ______________________ Date ______________________

Title or Position ______________________ National Forest/Region ______________________

Questions 1-13 can be answered with a Yes/No answer and followed with any additional comments, whereas 14-16 require written comments and information.

QUESTION	YES/NO	COMMENTS
1. Are there any particular problems that you have experienced using LVR?		See Summary
2. If so, has this problem been corrected?		
3. Has computer access, or excess program execution time been a problem?		See Summary
4. Do you have problems determining inputs for LVR?	Yes - 3	
5. Has the User's Manual been satisfactory?	Yes - 10 No - 1	
6. Do you feel that you are getting results from LVR that are compatible with previous experience?	Yes - 9 No - 3	
7. Are there any changes that you would like to see in the current version of LVR?		See Summary
8. Are there any additional capabilities that you would like to see in LVR?		See Summary
9. What feature of LVR has proved most satisfactory to you?		See Summary
10. After a period of program usage, were the training sessions conducted by University of Texas staff satisfactory?	Yes - 13	
11. Do you feel it would be worthwhile to conduct additional training sessions in the future?	Yes - 7 No - 3	
12. Do you plan to expand your usage of LVR in the future?		See Summary
13. Do you feel LVR should become part of Forest Service procedure on a national basis?	Yes - 15 No - 2	

7/25/78

14. The following questions refer to models or capabilities within LVR:

a. Which output format for costs do you prefer (input card No. 2)?

Dollars/Square Yard? 1

Dollars/Mile? 5

or, Both Above? 8

b. For aggregate loss, do you prefer the user defined input of inches/MBF or the Lund model in the program (input card No. 4)?

Inches/MBF - 9 Both - 3

Lund Model - 1 No Data - 2

c. How often do you use the non-traffic deterioration parameters (input card No. 3)?

Often - 5

d. Do you use the deflection model design option (input card No. 2)?

Yes - 1 Will in Future - 8 No - 5

e. How often do you use the vehicle operating cost parameters (input card No.10)?

Often - 7

Seldom - 7

f. Do you use the user delay cost options (input card No. 8 and 9)?

Yes - 4

No - 10

g. How often do you analyze a new design over an existing road (input Card No. 2)?

Often - 13

Seldom - 1

15. Types of facilities designed using LVR?

a. Aggregate surfaced roads 140 miles ________ construction cost

b. Asphalt concrete roads 245 miles ________ construction cost

Comments: These are rough estimates, do not have good cost figures.

16. What evidence of cost savings have you noted on a:

a. Design basis (time, manpower, etc.) - Comments: ________

b. Project basis (better design strategy, resource allocation, etc.)
Comments: ________

The following questions should be rated on a scale of 1 - 5, where 1 is low or negative and 5 is high or positive.

QUESTION	RATING (1 - 5) AVERAGE
1. How important is a pavement management system in your Forest/Region?	4.1 (15 Responses)
2. Has LVR been useful as a pavement management system?	2.5 (10 Responses)
3. To what extent has LVR been used (implemented) in your Forest/Region?	2.0 (14 Responses)
4. How would you rate efficiency of LVR versus other methods you have tried?	3.6 (11 Responses)
5. How difficult is LVR to use? (1 is easy, 5 is very difficult)	2.7 (12 Responses)
6. How would you rate LVR overall? (1 is bad, 5 is good)	4.0 (13 Responses)

SUMMARY OF LVR QUESTIONNAIRE RESPONSES

NOTE: Most people questioned responded only to those questions which they felt were relative to them. This appendix is a summary of those responses.

1. ARE THERE ANY PARTICULAR PROBLEMS THAT YOU HAVE EXPERIENCED USING LVR?

-- Too long a wait between inputing data and getting outputs. (Mt. Hood/R-6)

-- Had 200+ seconds run using minimum thickness of 4 inches and maximum thickness of 11 inches for individual rehabilitation. (Clearwater/R-1)

-- Use of Aggregate Loss Model (R-1)

3. HAS COMPUTER ACCESS, OR EXCESS PROGRAM EXECUTION TIME BEEN A PROBLEM?

-- Have a terminal but have not yet been allocated time on it. (Wallawa-Whitman/R-6)

-- Access with telephone-type terminal has been a problem (Umpqua/R-6)

-- Must use computer fascilities in another state, but has not been a big problem. (Daniel Boone/R-8)

-- No terminal operation presently - will be corrected. (Monongahela/R-9)

-- Excess execution time for thick aggregate surfaced roads (R-1)

4. DO YOU HAVE ANY PROBLEMS DETERMINING INPUTS FOR LVR?

-- Some problems with maintenance and delay costs. (Umpqua/R-6)

-- Traffic volumes and mixtures (Deschutes/R-6)

5. HAS THE USER'S MANUAL BEEN SATISFACTORY?

YES - 10 NO - 1

-- User's Manual is ok for trained user, but not for occasional user. Some terms are unfamiliar. (R-2)

-- Could be improved with more discussion and typical values. (Mt. Hood/R-6)

-- For deflection model, would like inputs explained for Benkelman Beam data as well as for Dynaflect. (Superior/R-9)

-- Very good. (Daniel Boone/R-8)

-- Would like example coding forms with columns marked and variables labeled. (IPNF/R-1 and N. F. of Texas/R-8)

-- Card 3 needs clarification. Card 2 does not indicate thickness of existing layer. (Clearwater/R-1)

6. DO YOU FEEL THAT YOU ARE GETTING RESULTS FROM LVR THAT ARE COMPATIBLE WITH PREVIOUS EXPERIENCE?

-- LVR is usually conservative because actual maintenance is never equal to program assumptions. (R-2)

-- Felt that some designs designated as "unfeasible" by the program were really feasible. (Deshutes/R-6)

-- Aggregate loss and rut depth models tend to overdesign. (N. F. of Texas/ R-8)

-- Very satisfied. (Monangahela/R-9)

— Basic aggregate surfacing design method is conservative (R-1)

7 and 8. ARE THERE ANY CHANGES, OR ADDITIONAL CAPABILITIES THAT YOU WOULD LIKE TO SEE IN LVR?

-- Considerable attention will be required to keep the internal models up to date. If that is not done on a continuing basis, the program may become obsolete in 3 to 5 years. (R-2)

-- It would be very convenient to have an input for dust abatement separate from annual maintenance costs. (R-2)

-- Different types of seal coats (chip seal and fog seal). (R-2)

-- Since using Macadam mix with cinder subbase, frost heave is the single most important design consideration. Would like frost heave and drainage considered in design. (Deschutes/R-6)

-- Option to use only the thickness design portions, excluding the economics. (Mt. Hood/R-6)

-- Would like to see RDS interaction with LVR. (Superior/R-9)

-- Better information on operating cost, especially for asphalt vs. aggregate surface. (I.P.N.F./R-1)

-- Roads are usually designed for worst condition, but F.S. can usually shut the loggers off when this happens. Would like way to scale down design for this. (Clearwater/R-1)

-- Would like to run aggregate and asphalt surface in one run. Also feel that multiple chip seals should increase structural number. (N. F. of Texas/R-8)

-- Better deflection model. Will be using this method more in future. (Monangahela/R-9)

-- Compare aggregate surface design directly with paved, also need to improve method for designing seal coating directly on aggregate base. (R-1)

-- More emphasis on deflection design. (Umpqua/R-6)

-- Capability to handle very low volumes of traffic. (R-8)

-- Better procedure for determining regional factor. (R-8)

-- Suggest the output be simplified as is sometimes confusing to new users. Only really need the summary sheet. (R-1)

-- In this region it is vital that varying earth quantities for different surfacing designs be calculated in the total cost of each alternative. (R-6)

9. WHAT FEATURE OF LVR HAS PROVED MOST SATISFACTORY TO YOU?

-- Nonlinear traffic model is essential. (Deschutes/R-6)

-- Likes input options for user defined data. (Superior/R-9)

-- Different design options. Is much better than Chapter 50. (Daniel Boone/R-8)

-- Better evaluation of all options. (Umpqua/R-6)

12. DO YOU PLAN TO EXPAND YOUR USAGE OF LVR IN THE FUTURE?

YES: 18 NO: 4

-- It is not ready for everyday use on a production basis. (Mt. Hood/R-6)

-- Most planning occurs in fall, intend to use a lot this year. (Superior/R-9)

-- With low volumes and mainly recreational traffic in Alabama, does not seem that computer application is necessary. Much better for Western Regions with more traffic and revenues. (N. F. of Alabama/R-8)

-- Have our own Pavement Mangement System we use. (Deschutes/R-6)

— Yes, as designers become more proficient in its use (R-8)

14. b. AGGREGATE LOSS

-- Should be some way to handle losses due to recreation and non-timber traffic. (R-2)

-- Have any Forest Service studies of aggregate loss been completed? (N. F. of North Carolina/R-8)

-- Should have more information on gravel loss, especially as a function of gravel type and gradation. Is important in Forest Service contracts. (Medicine Bow/R-2)

16. WHAT EVIDENCE OF COST SAVINGS HAVE YOU NOTED ON A:

a. DESIGN BASIS

-- Once a designer has convinced his forest engineer that the LVR solution is valid, and once the designer has mastered the input procedures, a much more satisfactory design is possible. We are only part way there; saving time is so far not appreciable. (R-8)

APPENDIX E

SUMMARY OF TECHNICAL MEMORANDA

APPENDIX E. SUMMARY OF TECHNICAL MEMORANDA

During the course of Phase III it was often necessary for project staff members to write technical memorandums concerning pertinent items of development. In this appendix the more important memorandums have been summarized to give the reader more information about particular subjects of interest.

PAVEMENT FAILURE TEST FOR TOP LAYER

Program LVR uses several criteria to determine pavement failure time. In multi-layered pavement strategies the program checks the failure time of the top layer using the soil support value for the second layer as the SS value for the subgrade. This is done to insure that, regardless of the structural strength of the entire pavement, the top layer must last the minimum time between rehabilitation.

Presently, this scheme works well for an ACP surface but is not applicable to an aggregate surfaced road. An aggregate surfaced road need not have this constraint since having the top layer deteriorate merely means that traffic will ride on some other aggregate surface. Other failure conditions are still in operation to insure that the time to failure of a given strategy is computed correctly using traffic and the structural strength of the multi-layered pavement.

AGGREGATE PAVEMENT DESIGN

A request was received from C. C. Ketcham, Director of Engineering, Region 8, on clarification of Equation 10, page 20 of Phase II - Forest Service Report. As a matter of record, attached is a copy of Mr. Ketcham's letter of June 6, 1977. In the letter Mr. Ketcham requested that we:

(1) Respond to the question of whether in low CBR soils, the two wheels in a dual act independently or not and whether P and A in Eq 10 of FS-II Report (Ref) should be 4500 pounds and 56.25 square inches respectively, instead of 9000 pounds and 112.5 square inches.

(2) Respond to the complaint from Forest Service Engineers that pavement thicknesses for aggregate surfaced roads are approximately 50 percent greater than local experience indicates is necessary for adequate performance.

Response to Question (1)

Even though the two wheels on a dual will rut separately in low CBR soils, the pavement thickness required is that to prevent overstressing of the subgrade soil. Therefore, the issue is one of stress level in the subgrade. Since there is an overlapping of stress due to the immediate proximity of the dual wheels, there appears to be no reason for justifying that the duals act as independent loads. This independence is necessary to permit the reduction of the load from 9000 pounds on a set of duals to 4500 pounds on a single tire of a set of duals. It is true that in the Corps of Engineers report (Technical Report S-70-5, Ref 2) upon which Eq 10 was based, there were no dual tire configurations; however, the tires used in the testing were 20 inches wide and a set of normal tires used in duals has about the same width. It appears that this extrapolation from a single tire to dual tire loading is not unreasonable.

Response to Question

In order to respond appropriately to question (2), we must trace the development of the Forest Service aggregate thickness model. The original data used by Ron Williamson to develop the aggregate thickness model were obtained from a 1970 Corps of Engineers Report. In the study, the Corps was developing an equation for predicting required thickness for aggregate-surfaced airfields and pavements. Full-scale tests were conducted over several clay subgrades with CBRs ranging from two to four. The Corps data on coverages sustained to failure (defined by Corps as development of a three-inch rut in the surface) were recorded and a regression model to predict thickness was developed and reported in Ref 2. These same data were used by Ron Williamson to develop the Forest Service thickness design equation, except that Ron used the development of a two-inch rut as the failure criterion. What Ron developed, indirectly, by using coverage data for development of a two-inch rut, was, in essence, practically the same thickness equation as used by the Corps for flexible pavements (this information was relayed by Ron in a telephone conversation on June 20, 1977. Ron had only recently become aware of this fact.)

The Corps of Engineers' flexible pavement design equation is:

$$t = (0.23 \log C + 0.15) \sqrt{\frac{P}{8.1\ CBR} - \frac{A}{\pi}} \qquad \text{(Ref 2, Page 13)}$$

The equation developed by Ron Williamson of the United States Forest Service for two-inch rut in aggregate surface roads is:

$$t = (0.216 \log C + 0.1705) \sqrt{\frac{P}{8.1\ CBR} - \frac{A}{\pi}} \qquad \text{(Ref 1, Page 20)}$$

One can see that there is very little difference between these two equations. The terms under the radical are the same and the constants in the first and second term are nearly the same. The difference for a few conditions are shown as follows:

Conditions:

C = number of coverages (C is assumed by Williamson to be equal to the number of 18-kip SAL for highway conditions)

Tire pressure = 80 psi

P = 9000 pounds

CBR = 1, 5, 10, 15, 20 and 25

$$C = 1000 \text{ 18-kip SAL}$$

F.S. $$f_{FS} = 0.216 \log C + 0.1705 = 0.216 \log(1000) + 0.1705$$

$$f_{FS} = 0.8185$$

Corps $$f_{ce} = 0.23 \log C + 0.15 = 69 + 0.15$$

$$f_{ce} = 0.84$$

Difference in the Forest Service aggregate model and Corps of Engineers' paved model is in the term f and amounts to a difference of

$$\text{percent} = \frac{0.84 - 0.8185}{0.84} \times 100 = 2.56 \text{ percent}$$

therefore,

Conclusion: The aggregate model as developed by the Forest Service probably overdesigns aggregate roads. In the Corps' report, S-70-5 (Ref 1) the following quote is noted:

Part VI: Conclusions and Recommendations

Conclusions (Paragraph 32)

"The curve and equation developed from this investigation indicate that thickness requirements for unsurfaced roads and airfields are approximately 75 percent as great as those determined by the flexible pavement design curve and equation. This can be partially explained by the difference in the failure cirteria for flexible pavement surfaced and unsurfaced areas."

Note: The failure criteria used in this report (S-70-5) was the formation of a three-inch rut. One would be led (even though the Corps does not say what the flexible pavement failure criteria is) to believe that a two-inch rut was the failure criteria for the paved (flexible pavement) surfaces. This conclusion is arrived at because of the correspondence between the thickness requirements from the Corps' flexible pavement model and the two-inch rut depth Forest Service aggregate surfaced model.

Conclusion

One cannot justify reducing the load P to 4500 pounds because, even if there are two separate ruts formed under the duals, there will be overlap of stresses underneath the wheels. However, it does appear that some alteration in the Forest Service thickness design equation is in order, since the thickness from the existing model yields thicknesses compatible with requirements for an asphalt-surfaced road.

Corps of Engineers' three-inch rut criterion thickness failure design equation is:

$$t = \underbrace{(0.176 \log C + 0.120)}_{f_{3''rut}} \sqrt{\frac{P}{8.1\ CBR} - \frac{A}{\pi}} \qquad \text{(Ref 2, Page 16)}$$

$$f_{3''rut} = 0.176 \log C + 0.120$$

for the previous example:

$$C = 1000 \text{ 18-kip SAL}$$

$$P = 9000 \text{ pounds}$$

$$p = 80 \text{ psi}$$

$$f_{3''rut} = 0.176 \log (1000) + 0.120 = 0.528 + 0.120 = 0.648$$

Table 1 demonstrates the effect of these different equations on required thickness of material over the subgrade.

Citing (1) the previous quote from Corps report S-70-5 and their willingness to accept a 25 percent reduction in thickness when going from the asphalt-surfaced condition to the aggregate-surfaced condition and (2) the

TABLE 1. REQUIRED THICKNESS OF MATERIAL OVER THE SUBGRADE FOR DIFFERENT MODELS

CBR	t_{FS} 2"rut (inches)	t_{CE} flexible (inches)	t_{CE} 3"rut (inches)	Percent Change 3" ⟶ 2" rut Aggregate Surface
1	26.8	27.5	21.2	20.9
5	11.2	11.5	8.8	21.4
10	7.1	7.3	5.6	21.1
15	5.1	5.2	4.0	21.6
20	3.6	3.7	2.9	19.4
25	2.4	2.5	1.9	20.8
				125.2

Average Difference 20.9 percent

evidence from Forest Service practice that thinner aggregate-surfaced roads perform adequately in the field, it is recommended that the thickness model used in LVR be changed.

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
1720 Peachtree Road NW Room 720
Atlanta, Georgia 30309

7170

Dr. B. Frank McCullough
University of Texas
200 West 21st Street
Austin, Texas 78712

JUN 6 1977

Dear Dr. McCullough:

With reference to your telephone conversation on May 27, 1977 with Doug Scholen, Region 8, Materials Engineer, we would like to have your opinion on the use of a 4500 pound wheel load in equation 10 of the final report for Phase II of the LVR program.

In practice, an 18,000 pound axle is supported on four wheels, or 4500 pounds are supported per wheel. When this value is substituted in the radical of equation 10, the resulting value differs from that of the 9000 pound load, as shown in the following tabulation.

CBR	P = 9000	P = 4500	Difference
1	32.79	23.19	9.6
5	13.65	9.66	4
10	8.68	6.14	2.5
15	6.19	4.37	1.8
20	4.44	3.14	1.3
25	2.94	2.08	0.9

Note the substantial difference in the lower CBR range.

Users of Chapter 50 complain that the pavement thickness required by this equation is often 50 percent greater than local experience indicates. Since the subgrade CBR of many Forest roads ranges from five to ten, the present interpretation of wheel loading, e.g., 9000 pounds, could be the reason. The stronger soils tend to bridge the load from dual wheels, effecting a single load on the subsoil. Weaker soils cannot do this and will form two ruts under the duals, with soil forced up between the tires. This condition must be considered in low CBR soils.

Sincerely yours,

C.C. Ketcham.
C. C. KETCHAM
Director
Engineering

cc: W.O. (Adrian Pelsner)

CHANGES MADE TO LVR PROGRAM

Cumulative Traffic Model

Recent attempts to use the LVR program for two aggregate surface design problems failed because of time-limit aborts. It was then discovered that the iterative algorithm in the RUTT subroutine could not converge given the way it employs the array CUM18K - the cumulative equivalent 18 KIP single axle loads (ESAL) which is input by the user.

The function of RUTT is to compute the time T when two-inch ruts occur. Given an initial layer structure and a starting time T_o the algorithm performs the following steps during each iteration:

(1) Compute $D = F_d(T_i)$, the resulting effective layer thickness which depends on aggregate loss and thus time.

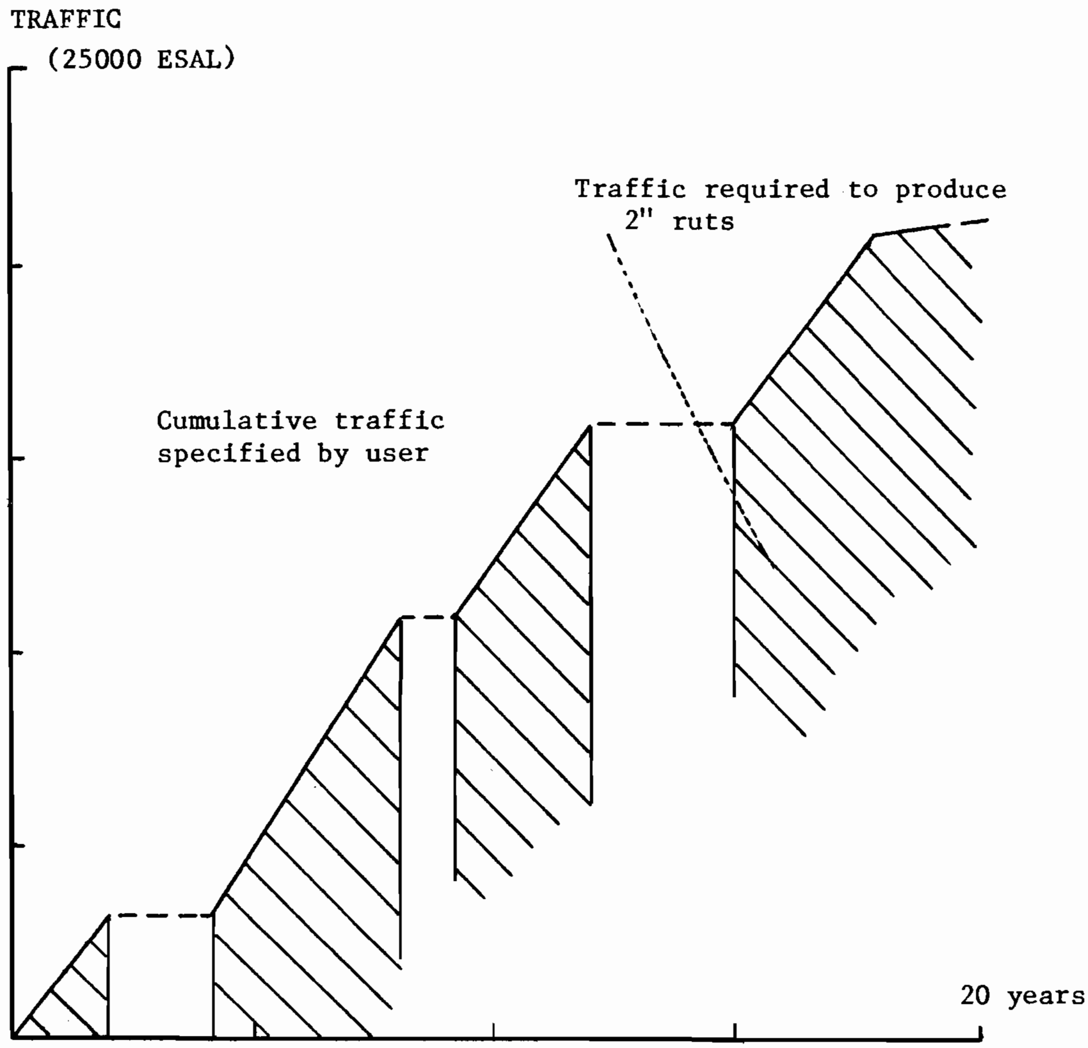
(2) Compute $K = F_k(D)$, the cumulative traffic (ESAL) necessary to produce two-inch ruts for thickness D.

(3) Use the CUM18K array to determine a time $T' = F_t(K)$ for the amount K traffic to a accumulate.

(4) If the magnitude of $T' - T_i$ is less than 0.1 set $T = T_i$ and exit subroutine. Otherwise increment (or decrement) T_i as appropriate and go to step 1.

The above procedure can fail if the involved functions are not continuous. In particular, if the user-defined cumulative traffic (ESAL) is not a strictly increasing function of time, then its inverse F_t (step 3) is discontinuous. In this case the function F_t cannot return values within certain time intervals, and depending on the location of cruve F_k $(F_d(T))$ the condition in step 4 might never be satisfied. The problem is illustrated graphically on the following page.

These situations can be avoided most simply by giving a slight positive slope to the CUM18K curve over those periods for which the user actually specified no change. Thus, the following code was inserted immediately after the statement labeled 78 in the INPUT subroutine:



Example Problem - Homestead Road

```
DO 90, I = 1, ITEMP
IF(CUM18K(I + 1).LE.CUM18K(I)) CUM18K(I + 1) =
. CUM18K(I) + TIMNL(I + 1) - TIMNL(I)
90 CONTINUE
```

The effect of this is to provide one ESAL per year over certain intervals to insure a positive slope. Since the modification occurs only after the input data is summarized in the listed table, the effect will not be noticed by the user although it has shown to be sufficient to force the algorithm in RUTT to converge.

Routine USERAG

This portion of the program is bypassed unless the user elects to have aggregate loss determined by amount of lumber hauled, etc. rather than by the Lund model (routine AGTBL). In USERAG the cumulative aggregate loss function is derived piecewise from the following input data:

(1) loss in inches for each unit (1000 BDFT) of lumber hauled during a time interval,

(2) number of units hauled, and

(3) ADT (trucks) at intervals' start and finish.

Thus, (1) and (2) determine the total amount of loss and (3) determines how it is to be proportioned over the interval. Since ADT is assumed to vary linearly between time points and rate of loss is taken to be proportional to ADT, the resulting cumulative loss within a particular interval is a quadratic function of time.

The purpose of USERAG is to approximate this function with an array (ALOSS) of values taken at 0.2 year intervals. The original version failed because variables were not properly initialized and because total cumulative truck traffic instead of incremental increase was used to compute incremental loss. Ordinarily this would inflate the loss; however, the routine also disregarded any loss specified by (1) and (2) if the time interval were less than 0.2 years. In one set of data prepared by Forest Service personnel ("Homestead Road") most of the loss occurs within several 0.1 year periods.

In the rewritten version of USERAG preference is given to the user-defined arrays BDFT and BDFTIN of (1) and (2) above. Hence, if the user inputs a nonzero loss of AGL = BDFT(I) * BDFTIN(I) for the interval TIMNL(I + 1) - TIMNL(I), the cumulative loss will increase by AGL even if he inconsistently specifies zero truck traffic (in which case ALOSS will resemble a step funciton). The next revision of the user's guide will point out that with this option the values input for truck ADT determines the rate (but not the amount) of aggregate loss between time points.

Initialization of Variables

Additional code changes in routine LVR were necessary to prevent fatal arithmatic errors when running the MNF compiled program. Since MNF presets (by default) arrays to negative indefinite, execution can abort if arithmetic is performed on variables which are not defined in the program. These particular cases involved superfluous computations which would not have affected the printed output if the program had run.

Default Value for IFC

The IFC parameter (card No. 3) currently takes values 1 thru 4 and specifies whether the road has fills, side casts, cuts, or is equal in cuts and fills. The default now in effect for this parameter (when the Lund model is chosen) is IFC = 4 : equal in cuts and fills. The user will not be notified in this selection because the relevant messages are printed before the test is performed to determine whether AGTBL or USERAG will be called to compute the aggregate loss table (IFC is not used in the latter). This test examines the BDFT array for nonzero quantities.

CODE CHANGES IN PROGRAM LVR10

To locate the revised sections of code in each subroutine note the unchanged FORTRAN statements which have been included to provide context. Modified or inserted code has been underlined whereas old code which does not appear within a segment of statements has been deleted. Dotted lines are used to abbreviate portions that are unchanged.

Program LVR:

```
      C   THE MATERIAL COMBINATIONS FOR THE ALTERNATIVE DESIGNS
      C
          DO 15 I=1,40
          DO 15 J=1,55
       15 POLICY(J,I) = 0.0
          DO 30 I=1,11
          XINC(I) = 0.0
          NN(I) = 0
       30 NMBMAT(I) = 0
```

Subroutine INPUT:

(1)

```
      C
          DIMENSION XXJ(11),ILAYER(11),ISEC(4,5)
          DIMENSION DEFLP . . . . .
```

(2)

```
          DATA ISEC / . . . . . . . .
         1       6HWITH . . . . . . . . . . ,5H FILL,
         2       1H ,1H ,1H ,1H /
      C
```

(3)

```
      10000 FORMAT(2X,9H* INPUT * )
          IF(IFC.LT.1.OR.IFC.GT.5) IFC = 5
          IF(DATA(1,11).LT.1.0) GO TO 72
```

(4)

```
          79 CONTINUE
             IF(IFC.GT.4) IFC = 4
             CALL AGTBL
          80 . . . . .
```

Subroutine USERAG:

```
(1)     10000 FORMAT(2X,10H* USERAG * )
              NALOSS = TIMNL(NNL)*RH + 1.0
              IF(NALOSS.GT.2000) GO TO 70

(2)     C   IN THE ITH PASS THROUGH THE FOLLOWING LOOP, TABULATE THE AGGREGATE
        C   LOSS BETWEEN TIMNL(I) AND TIMNL(I 1).
              SLOPE = 1.0
              DO 30 I = 1, NM1
              AGL = BDFT(I)*BDFTIN(I)
              SAVE = SAVE + AGL
              TIME = TIMNL(I+1)
              CALL CUMTRF(TRAF1,TIME,2)
              IF(TRAF1.LE.TRAF0) GO TO 15
              SLOPE = AGL/(TRAF1-TRAF0)
           15 IF(T+H.GT.TIME) GO TO 20
              T = T + H
              CALL CUMTRF(TRAF,T,2)
              J = J + 1
              ALOSS(J) = ALAST + SLOPE * (TRAF - TRAF0)
              GO TO 15
           20 ALAST = SAVE
              TRAF0 = TRAF1
           30 CONTINUE
              ALOSS(J+1) = ALAST
              RETURN
           60 FORMAT( . . . . . . . . .
             1E DIMENSIONED . . . .
           70 PRINT 60, NALOSS
```

Rehabilitation Strategy for Aggregate Surfaced Roads

At least two users of the LVR program have had difficulty in obtaining feasible designs for aggregate surfaced roads. They found that by increasing the maximum layer thicknesses for initial construction they could get a design that would last the entire analysis period. There were no designs, however, that allowed for aggregate additions.

The problem arose because of inconsistencies in the program code which examines a layer configuration to determine how long it will last. For aggregate designs the time to failure is defined by the current LVR model to be the minimum of two times:

(1) the time when thickness is reduced to a specified minimum by aggregate loss,

(2) the maximum of (a) the time when rut depth equals two inches according to the modified U. S. Army Corps of Engineers structural model and (b) the time that serviceability (PSI) is too low according to the AASHTO performance model.

An inspection of subroutines SOLVE2 and OVRLAY revealed that the AASHTO and rutting models were not used in a manner consistent with (2). Instead, the unmodified AASHTO equation (without swelling clay parameters) was employed as a screening device to reject beforehand any design whose structural number is too small for it to last the minimum time to the next rehabilitation. Only when the layer thicknesses had been incremented to meet this criterion were both models used as indicated above to derive the time when rehabilitation would be necessary.

This strategy has led to unexpected results because the rutting model is sometimes considerably less restrictive than the performance model and may give a long time to failure (longer than the analysis period) for every design allowed by the latter via the screening process. Consequently, no feasible designs requiring a rehabilitation will be presented.

The program code had to be revised so that the different road deterioration models interact appropriately as designs are generated (by incrementing layer thicknesses) and then tested. In effect, the screening process described above will be performed only for paved roads.

LVR-10 CODE REVISIONS (01/13/78)

The following revisions will affect only the applications to aggregate surfaced roads. New or modified FORTRAN statements are underlined.

Subroutine SOLVE2:

```
      ......
      CALL TIMTRF(W,TIM)
      IF(TIM.LT.XTTO(1).AND.ITYPE.EQ.1) GO TO 117
      IF(TIM.GE.TMIN) GO TO 190
      ......

      ......
  114 IF(ITYPE.EQ.1) GO TO 115
      ISW = 0
      AL = DOVER(1) - TLMIN
      ......
```

Subroutine OPTIML:

```
      ......
      IF(ITYPE.EQ.1) GO TO 320
      ISW = 0
      AL = DOVER(1) - TLMIN
      ......
```

Subroutine OVRLAY:

```
      ......
      CALL TIMTRF(WW,TIM)
      TM = TIM - TPRIM
      IF(TM.LT.XTTO(I).AND.ITYPE.EQ.1) GO TO 115
      IF(TIM.GE.TMIN) GO TO 110
      ......

      ......
  113 IF(ITYPE.EQ.1) GO TO 114
      ISW = 0
      AL = DOVER(1) - TLMIN
      ......
```

Subroutine AGTBL:

```
      ......
10000 FORMAT(2X,9H* AGTBL *)
      NALOSS = TIMNL(NNL)/H + 1.0
      IF(NALOSS.GT.2000) GO TO 40
      ......
```

Subroutine TALOSS:

```
      ......
      IF(JK.LT.2) JK = 2
      TL = H*(JK-2)
      IF(AL.LE.ALOSS(JK-1)) RETURN
      DO 10 J = JK, NALOSS
      ......
```

EFFECT OF NON-TRAFFIC DETERIORATION PARAMETERS

Definition of Terms and Numerical Values Used for Calculations

SN - Structural number based on AASHTO performance equation reported on Phase II Research Report 43. (Used values 1 to 5)

P_1 - Serviceability Index after an overlay. (Used values 4.5, 4.2, 3.8)

P_2 - Terminal Serviceability Index. Point at which rehabilitation must be performed. (Used values 1.5, 2.0, 2.5)

b_1 - Swelling Clay Parameter. A non-traffic deterioration parameter. (Used values 0.0, 0.06, 0.12)

XTTO - Minimum length of the first performance period in years. This is the length of time between initial construction and first major rehabilitation. (Used values 20.0, 2.0)

NOTE: Rest of variables dealing with the AASHTO performance equation stayed at "AVERAGE" value.

Objectives

The main purpose of this study was to analyze the effect of P_1, P_2, and b_1 on the Structural Number working through the AASHTO performance equation, making comparisons between SN assumed and calculated.

After that, it was necessary to observe the effect reducing the length of the first performance period.

Based on those calculations, it was decided to analyze the effect of the variables and combinations on the pavement structure total overall cost.

Analyzed Combinations for P_1 and P_2

The following combinations were performed by hand calculations and computer runs:

(1) Low P_1, Ave P_2

(2) Ave P_1, Ave P_2

(3) High P_1, Ave P_2

(4) Ave P_1, Low P_2

(5) Ave P_1, High P_2

In order to analyze the overall effect of P_1, P_2 and b_1 on SN with XTTO = 20, it was decided to perform the complete calculations by hand, getting results, plotting them and comparing the SN assumed versus the SN calculated. After that, it was necessary to make computer runs in order to check results.

In the first trial for $b_1 = 0.06$, it was noticed that when working with low and high values of b_1, there was a combination giving negative numbers on which calculations were not possible to solve, because of the original equation changed to a logarith form.

When using $b_1 = 0.06$, there was no problem in the analyzed combinatioas of P_1 and P_2 except "Ave P_1 and High P_2" condition, where hand solution and computer run output were not obtained. In that calculations, when plotting SN assumed versus calculated, the curve's shape (involving different trials from 1 to 5), never touched the 45 degree line. That means, there was not a

SN value at which the assumed coincided with the calculated. From the computer output, it was obtained a printed message informing that the minimum time between overlays was too long.

When using $b_1 = 0.12$, all combinations for P_1 and P_2 except "Ave P_1, Low P_2", had no results through hand calculations, and computer runs, because of the negative differences between g and g' (with the involved variables P_1, P_2, b_1 and (XTTO). So, there was no solution for negative logarithms.

When working with $b_1 = 0$, there was not any problem dealing with the analyzed combinations.

NOTE: All performed calculations by hand were checked and compared with computer output runs.

Summary

The length of the first performance period becomes critical when using $b_1 = 0.12$.

Analyzed Combinations for P_1, P_2 and b_1 Reducing XTTO to Two Years

When working with the previously mentioned combinations in the above section of this technical memorandum, but reducing the length of the first performance period to two years, it was found that there is no problem at all. Every combination of variables was working well (for one, two and three layer designs), getting the adequate Structural Number.

An interesting observation was found here. The computer time cost per run was increased up to four times when b_1 varied from 0 to 0.12. That means the average cost was one dollar/run when using $b_1 = 0$. On the other hand, the average cost for $b_1 = 0.06$ was three dollars and \$3.76 when $b_1 = 0.12$ was used, exceeding the four dollars some times.

Summary

The computer time cost could be increased up to four times when the swelling clay parameter value differs from zero ($b_1 \neq 0$).

Cost Comparison for the Analyzed Combinations

Based on the computer outputs for the mentioned conditions in the above section, it was found that there is not significant effect on the pavement structure total overall cost (combining P_1 and P_2, modifying b_1 and keeping constant XTTO equal to two years).

Between $b_1 = 0$ and $b_1 = 0.12$, it was found a maximum difference of \$6,000 working with "Ave P_1 and High P_2" and a minimum difference of \$3,200 working with "Ave P_1 and Low P_2" condition.

Summary

There is not significant effect of the analyzed variables and combinations, working with the established values, on the pavement structure total overall cost.

DEFLECTION DESIGN CRITERION FOR FLEXIBLE PAVEMENTS

In accordance with the instructions from M. R. Howlett, Director of Engineering of the U. S. Forest Service, we are including a deflection design procedure in the LVR pavement management program. The deflection design procedure is based on one proposed by R. Ian Kingham titled "Development of the Asphalt Institute's Deflection Method for Designing Asphalt Concrete Overlays for Asphalt Pavements," Research Report 69-3, June 1969, Asphalt Institute Building, College Park, Maryland 20740.

Description of the Thickness-Deflection Relationship

Numerous references in the technical literature point to the fact that elastic theory can be used to predict pavement defleci-on. If the pavement is assumed to act as a unit that can be tested in some manner to produce an estimate of the aggregated or effective elastic modulus, the following two-layer equation is appropriate for estimating surface deflections:

$$d_c = \frac{1.5\ pa}{E_S} \left[\left(1 - \frac{1}{\sqrt{1 + (0.8\ \frac{t}{a})^2}} \right) \frac{E_S}{E_P} + \frac{1}{\sqrt{1 + \left(0.8\ \frac{t}{a} \sqrt[3]{\frac{E_P}{E_S}}\right)^2}} \right] \quad \ldots \text{Eq 1}$$

where

d_c = the deflection at the surface, inches (For design there is an allowable deflection, d, that is limited because of fatigue problems)

p = tire contact pressure, psi

a = radius of the contact area, inches (assumed to be round)

t = pavement thickness, inches

E_P = pavement elastic modulus, psi (can be considered to be the resilient modulus, M_R)

E_S = subgrade elastic modulus, psi, and represents the foundation support for the asphalt concrete overlay. This modulus is assumed to be related to the representative rebound (RR) by the Boussinesq equation:

$$RR = d = \frac{1.5\ pa}{E_S} \quad \ldots \text{Eq 2}$$

The representative rebound is assumed equal to the allowable design deflection where:

$$RR = SF\ (\overline{D}_r + 2S) \quad \ldots \text{Eq 3}$$

$\overline{D}_r$ = Average Benkleman Bean rebound deflection corrected to a temperature of 70°F

S = standard deviation of the deflection data

SF = a Season Factor as explained in the Asphalt Institute Manual Series, MS-17.

The representative rebound deflection is determined in the field from Dynaflect readings taken at several stations along the roadway. The actual deflection at the first geophone, D, of each station is calculated. This deflection at the first geophone has been correlated by regression with Benkleman Beam rebound, D_r, using a second order polynomial with a coefficient of correlation equal to o.826. The regression analysis involved 176 points resulting in the following equation:

$$D_r = -939.7084\ D^2 + 25.80064\ D + 0.002063 \qquad \ldots \text{ Eq 4}$$

where

D = actual deflection at the first geophone of the Dynaflect

D_r = estimated Benkleman Bean rebound deflection

This estimated rebound deflection must be corrected for temperature deviation from 70°F by the following formula:

$$\text{Corrected } D_r = D_r + \frac{70^{\circ} - t}{5000} \qquad \ldots \text{ Eq 5}$$

where

t = Pavement temperature during Dynaflect test in degrees F.

Corrected D_r = Temperature corrected Estimated Rebound Deflection rounded to 4 significant figures.

NOTE: Equations 4 and 5 and the discussion were obtained from Mr. Ron Williamson of Region 6 in Portland, Oregon via personal correspondence.

Substituting Eq 2 into Eq 1 in the form of $E_S = \frac{1.5\ pa}{RR}$, Eq 6 results:

$$d_c = RR\left[\left(1 - \frac{1}{\sqrt{1 + (0.8\ \frac{t}{a})^2}}\right)\frac{1.5\ pa}{(RR)E_P} + \frac{1}{\sqrt{1 + \left(0.8\ \frac{t}{a}\sqrt[3]{\frac{(RR)E_P}{1.5\ pa}}\right)^2}}\right] \quad \text{... Eq 6}$$

The required input data for use of Eq 4 in LVR are:

(1) $\overline{D}_r$, m and S ----- RR = $\overline{D}_r$ + mS where m = No. of standard deviations above the mean, selected for a prescribed risk level.

----- default value for m = 2.0 (see Figure VI ordinate label)

(2) p --------------- default value = 70 psi

(3) a --------------- default value = 7.9 inch

(4) E_P --------------- default value = 500,000 psi

In order to relate the representative rebound, RR , to the number of 18 Kip equivalent single axle loads (S.A.L.), the relationship shown in Fig VI - Compilation of Beam Deflection Experience from Asphalt Institute Research Report 69-3, p 17 was used to obtain the following equation (Equation obtained by regression analysis from Ron Williamson, U.S.F.S., Portland, Oregon - Ref. personal correspondence):

$$\log_{10} d_c = -0.24364009959 \log_{10} \left(\frac{W_t}{7300}\right) - 0.926657021999 \quad \text{... Eq 7}$$

By taking the antilog of Eq 7, an equation for d_c can be obtained:

$$d_c = \left(\frac{W_t}{7300}\right)^{-0.243640} \times 10^{-0.926657} \quad \text{... Eq 8}$$

Solving Eq 7 for $\frac{W_t}{7300}$ gives:

$$\left(\frac{W_t}{7300}\right) = \left(\frac{d_c}{10^{-0.926657}}\right)^{\frac{1}{-0.243640}} = \left(\frac{d_c}{0.118398}\right)^{-4.10442}$$

$$\left(\frac{W_t}{7300}\right) = \left(\frac{0.118398}{d_c}\right)^{4.10442} \quad \text{... Eq 9}$$

Since $\frac{W_t}{7300}$ is the total number of 18 Kip SAL for a 20 year analysis period, make a change in the notation to produce the number of 18 Kip SAL per day for any analysis period:

W_t = Total number of 18 Kip SAL in the analysis period

ND = Number of days in the analysis period = 365 X No. of years.

Therefore Eq 7 becomes:

$$W_t = ND \left(\frac{0.118398}{d_c}\right)^{4.10442} \quad \text{... Eq 10}$$

In the present program, the process for starting with a minimum thickness of each layer and incrementing that thickness will permit a solution of d_c according to Eq 6. To determine if the design is acceptable the calculated surface deflection, d_c , will be compared to an allowable deflection, d , input by the user. If $d_c \leq d$, the design is acceptable. If $d_c > d$, the design may still be acceptable but only if the initial life exceeds the time to the first overlay. This initial life of the structure is calculated using Eq 10 and the non-linear traffic distribution model. If the initial life is less than the minimum specified, the candidate design is

Solving Eq 7 for $\frac{W_t}{7300}$ gives:

$$\left(\frac{W_t}{7300}\right) = \left(\frac{d_c}{10^{-0.926657}}\right)^{\frac{1}{-0.243640}} = \left(\frac{d_c}{0.118398}\right)^{-4.10442}$$

$$\left(\frac{W_t}{7300}\right) = \left(\frac{0.118398}{d_c}\right)^{4.10442} \qquad \text{... Eq 9}$$

Since $\frac{W_t}{7300}$ is the total number of 18 Kip SAL for a 20 year analysis period, make a change in the notation to produce the number of 18 Kip SAL per day for any analysis period:

W_t = Total number of 18 Kip SAL in the analysis period

ND = Number of days in the analysis period = 365 X No. of years.

Therefore Eq 7 becomes:

$$W_t = \text{ND}\left(\frac{0.118398}{d_c}\right)^{4.10442} \qquad \text{... Eq 10}$$

In the present program, the process for starting with a minimum thickness of each layer and incrementing that thickness will permit a solution of d_c according to Eq 6. To determine if the design is acceptable the calculated surface deflection, d_c , will be compared to an allowable deflection, d , input by the user. If $d_c \leq d$, the design is acceptable. If $d_c > d$, the design may still be acceptable but only if the initial life exceeds the time to the first overlay. This initial life of the structure is calculated using Eq 10 and the non-linear traffic distribution model. If the initial life is less than the minimum specified, the candidate design is rejected. In determining thickness for pavements consisting of materials other than ACP, I assume that a set of equivalencies similar to those of the AASHTO Flexible Design Procedure are appropriate.

COMMENTS:

1. This Procedure adopted by the Forest Service is appropriate ONLY for asphalt pavements. Since we have been instructed to use it for initial design, we cannot be absolutely confident of its appropriateness. In addition to these factors, one must recognize that some mechanism must be available to get from t (inches of ACP) to a a combination thickness of ACP and unbound granular materials. One procedure that could be used is based on the relative strength coefficients of materials, a's, as utilized in the AASHTO Interim Guide for Flexible Pavements.

Example: ACP has an a = 0.44

AASHTO crushed stone has an a = 0.14

Therefore 1 inch ACP is equivalent to 0.44/0.14 inches(3.14) of AASHTO crushed stone.

2. This design procedure is different in one basic respect from the other design procedures included in LVR in that it considers the stocastic variation in the deflection test data from which the representative rebound is calculated. Because none of the other models consider stocastic variation there is a question as to the appropriateness of the mixture of these two (2) types of models within the same program.

3. The correlation coefficient, R , for Eq 4 is only 0.826. This means that only 68.2% of the variation in Benkleman Bean Rebound deflections is explained by the deflection as measured by the Dynaflect. The real problem in using Eq 4 is that the calculated value for representative rebound appears directly in Eq 10 through Eq 6. Equation 10 has an exponential term with a power of 4.10442. The end result is that these unexplained variations present in the results of Eq 4 are being raised to a power of 4.10442. For Eq 10, the number of 18 Kip SAL (W_t) may be affected very dramatically by these variations.

For example:

A 10% variation in RR from 0.030 in. to 0.033 in. with $t = 3.0$ in., $a = 6.4$ in.^{2}, $p = 70$ psi and $E_p = 500{,}000$ psi produced the following values for W_t in Eq 10.

for RR = 0.030 $\quad W_t = ND(43{,}403)$

for RR = 0.033 $\quad W_t = ND(33{,}190)$

The variation in W_t of 23.5% for a 10% variation in RR indicates the sensitivity of W_t to variations (from errors in measurement, in correlations, etc) in RR.

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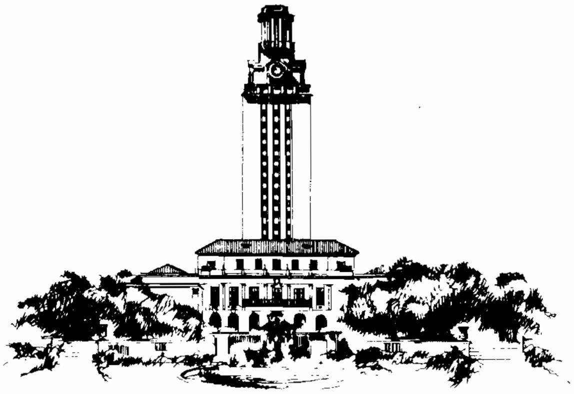

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