ATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 2

AN INTRODUCTION TO GUIDELINES FOR SATELLITE STUDIES OF PAVEMENT PERFORMANCE

IGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 2

AN INTRODUCTION TO GUIDELINES FOR SATELLITE STUDIES OF PAVEMENT PERFORMANCE

BY PAUL E. IRICK, PRINCIPAL INVESTIGATOR
HIGHWAY RESEARCH BOARD

HIGHWAY RESEARCH BOARD OF THE DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1964

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs the highway administrators of the American Association of State Highway Officials initiated in 1962, an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by Highway Planning and Research funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, non-profit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issuing from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

NCHRP Project 1-1 Advisory Committee

James H. Havens, *Kentucky Department of Highways*
Virgil L. Anderson, *Purdue University*
Robert F. Baker, *U. S. Bureau of Public Roads*
W. E. Chastain, Sr., *Illinois Division of Highways* (deceased)
Frank H. Scrivner, *Texas A and M University*

NCHRP Project 1-1, FY '63
NAS-NRC Publication 1201
Library of Congress Catalog Card Number: 64-60062

FOREWORD

By Staff
Highway Research Board

In recent years considerable effort has been devoted to the development of rational procedures of pavement design. One approach has been through research on large-scale road tests. Although several such tests have been conducted, the most recent and comprehensive was the AASHO Road Test at Ottawa, Illinois. All of these have been principally devoted to studying pavement design and its relationship to performance. They have involved investigations into the influence of designs, loads, materials, and climatic conditions. The results of these tests are applicable only to conditions comparable to those existing at the road test sites.

In order to achieve widespread utility for the research findings from the AASHO Road Test, it is necessary to translate them into local conditions. This may be done by small-scale road tests which can be considered as satellites to the one conducted at Ottawa. Studies for the translation may be made either on existing pavements or on newly constructed pavements. For the studies to be meaningful, guidelines are required to provide for uniform research studies so that comparisons may be made. Although individual studies may be conducted within states, it is also desirable to have related studies conducted regionally and on a nationwide basis.

This research project was undertaken to provide such guidelines. The final report contains principles and rules that can be used to design selected pavement sections and relate their behavior to similarly designed sections on the AASHO Road Test. In addition, the guidelines provide a basis for merging data of individual studies with data collected in the overall program. The paramount purpose of these guidelines is to provide means for translation of the Road Test findings to local conditions. They should also aid, however, in evolving design theories useful to all states.

The guidelines present a method of studying the interrelationships of performance variables and design variables. Three types of design variables are discussed: the structural variable which describes the strength characteristics of pavement layers, the load variable reported in terms of accumulated axle loads, and the climatic or regional variable which describes external influences. Performance variables are discussed in terms of surface behavior and include deformation and deterioration.

Report 2, "An Introduction to Guidelines," gives a brief, informative discussion of Report 2A, "Guidelines for Satellite Studies of Pavement Performance," and provides the perspective for this more technical treatise. The introduction discusses desired minimum basic measurements for satellite test installations and contains a statistical design for one typical test installation. Report 2A contains concepts, terminology and specific guides for experiment design, measurement programs and data processing. Illustrative studies are given for existing pavements and new experimental pavements. The appendices contain details about structural, load, climatic, and performance variables to be measured throughout the satellite studies, noting types of tests and measurements to be taken. Illustrations for a number of procedures for developing performance equations are given along with the performance index variables for all AASHO Road Test sections. The guidelines contain guides rather than "recipes" for the conduct of particular projects. They provide specific recommendations for coordination of satellite studies with one another and with the AASHO Road Test, yet maintain a flexibility in selection of pavement type and design in satellite installations.

Report 2A is provided in loose leaf Xerox format to allow for up-dating as experience gained in the future indicates needed modifications and additions.

This project is one of several relating to the extension of Road Test findings.

Other studies include the determination of factors influencing pavement performance regionally and locally, and an investigation into the extension of the AASHO Road Test performance concepts. A study is also under way to develop a prototype measurement team for obtaining standard measurements on the satellite program. It is expected that these research studies will ultimately provide a better knowledge and understanding of pavement design and a further utilization of the major findings of the AASHO Road Test.

The highway engineer will find these guides particularly useful in setting up individual studies whether they are on existing pavements or new experimental pavements. He will be able to include his studies in a nationwide program whereby an overall coordination and analysis is provided.

CONTENTS

AN INTRODUCTION TO GUIDELINES FOR SATELLITE STUDIES OF PAVEMENT PERFORMANCE

SUMMARY

This report summarizes and illustrates the general content of a much longer set of guidelines prepared for the conduct of pavement performance studies. These satellite studies deal either with existing pavement sections or with newly constructed experimental sections in the nation's highway system. Either type of study may be an individual project within one state or may represent the cooperative effort of a relatively large number of states on a nationwide scale.

The guidelines are written in terms of four classes of variables: structural, load, climatic or regional, and performance. Structural variables include thicknesses and strength characteristics of roadbed and pavement components. Two other structural variables are structural index and composite strength, where the structural index is used to reduce component strengths and thicknesses to a single scale and where composite strength is measured in terms of the pavement system response to a single load, such as deflections or strains.

Load variables are essentially in terms of equivalent 18-kip axle-load applications, using equivalence factors developed at the AASHO Road Test, and include rate of accumulation of the equivalent axle loads.

Climatic or regional variables include measures of rainfall and freeze-thaw characteristics as well as relative composite strengths of similar pavements (as-constructed) subjected to different climatic conditions.

Performance variables include measures of surface deformation and deterioration as well as present serviceability index values calculated from these measures. Also included is a performance index indicating the number of accumulated equivalent 18-kip axle-load applications which correspond to serviceability level 2.5 (on a scale from 0 to 5).

Activities in any satellite study are grouped in four classes: development of experiment designs, selection or construction of test sections, measurement of variables, and analysis of the measurements. The guidelines give many general and several specific guides for the conduct of any of the four activities. Much reference material from the AASHO Road Test is included and a number of hypothetical illustrations are used to demonstrate the use of the guidelines.

For individual satellite studies the guidelines recommend experiment designs which result in complete factorial experiments involving either two, three or four factors. Composite experiment designs are provided for nationwide studies of eleven factors over a wide range of variation in each factor. The nationwide experiment designs involve about forty test sites, with either two or five test sections at all except one site which has thirteen test sections. Principles of fractional replication are used to limit the number of sections needed for the nationwide studies.

The guidelines give general ground rules for the selection or construction of satellite test sections, but nearly all details are considered to be beyond their scope.

Recommendations are given for the measurement of structural, load, climatic, and performance variables. Minimal measurement programs are outlined, and

appendix material provides many details for evaluating variables in each of the four classes. It is recommended that measurement teams be equipped and trained to take "common denominator" measurements in the satellite program, ordinarily to supplement the measurement program of any individual sponsor.

Five types of analyses are discussed and illustrated in the guidelines: performance classification of test sections, direct comparisons with AASHO Road Test section performance, derivation or modification of mathematical relationships between performance and other variables, development of relationships between performance and composite strengths, and the testing of structural theories which relate composite strength to structural and load parameters.

INTRODUCTION

The main objective of the AASHO Road Test was to develop relationships between pavement performance and certain pavement design variables for a wide range of axle loads. It was recognized that the research findings related only to the specific structural materials, construction procedures, climatic conditions and loading conditions existing in the test.

A new series of pavement performance studies is now under way to determine the general applicability of these findings and what modifications may be needed for other than AASHO Road Test conditions. All these so-called satellite studies deal with sections of pavement located in the nation's system of highways. As indicated in Figure 1, some of the satellite studies involve the selection of sections from existing highways, whereas others involve the construction of new experimental sections at one or more locations in the highway system. Either type of study may be undertaken by an individual state, mainly to satisfy local objectives, or may represent the cooperative effort of a relatively large number of states on a nationwide scale.

At the request of AASHO, the National Cooperative Highway Research Program established a series of interrelated research projects to produce information that could be used in the satellite studies of pavement performance. These projects are in Area 1 of the NCHRP, and the first such project, Project 1-1, had as its objective the preparation of guidelines for the satellite studies. Other Area 1 projects involve techniques for evaluating pavement serviceability, the identification of factors which influence performance, reviews of theoretical pavement behavior, and techniques for standardizing satellite program measurements. It is assumed that results from these NCHRP projects can be merged with the individual and cooperative efforts of participating states and the Bureau of Public Roads to provide meaningful and efficient studies of pavement performance under a much wider range of conditions than existed in the AASHO Road Test.

The guidelines produced in Project 1-1 contain over two hundred pages of suggested rationale and procedures for the conduct of satellite studies. Much reference material from the AASHO Road Test is included, and hypothetical satellite studies are provided to illustrate the use of guides and reference material.

Advice for the report material was obtained from interviews with research engineers in the Bureau of Public Roads, in more than thirty state highway departments, and in several highway industries. In addition, a project advisory committee met on numerous occasions to review and discuss the material.

This summary report covers the general content of the guidelines, and includes a hypothetical satellite study to illustrate some of the more specific guidelines material.

GENERAL NATURE OF A SATELLITE STUDY

Any satellite study is considered to have four aspects whether the research is an individual or a nationwide study of either existing or new experimental pavements. These aspects (Fig. 2) are as follows:

1. Research objectives which might range all the way from simple comparisons of pavement performance to the formulation or testing of quite complicated theories of pavement behavior;
2. Variables involved with these objectives;
3. Activities governed by the objectives which deal with variables; and
4. Research findings which result from the activities and give information on one or more variables.

The guidelines are applicable to a wide range of research objectives and thus

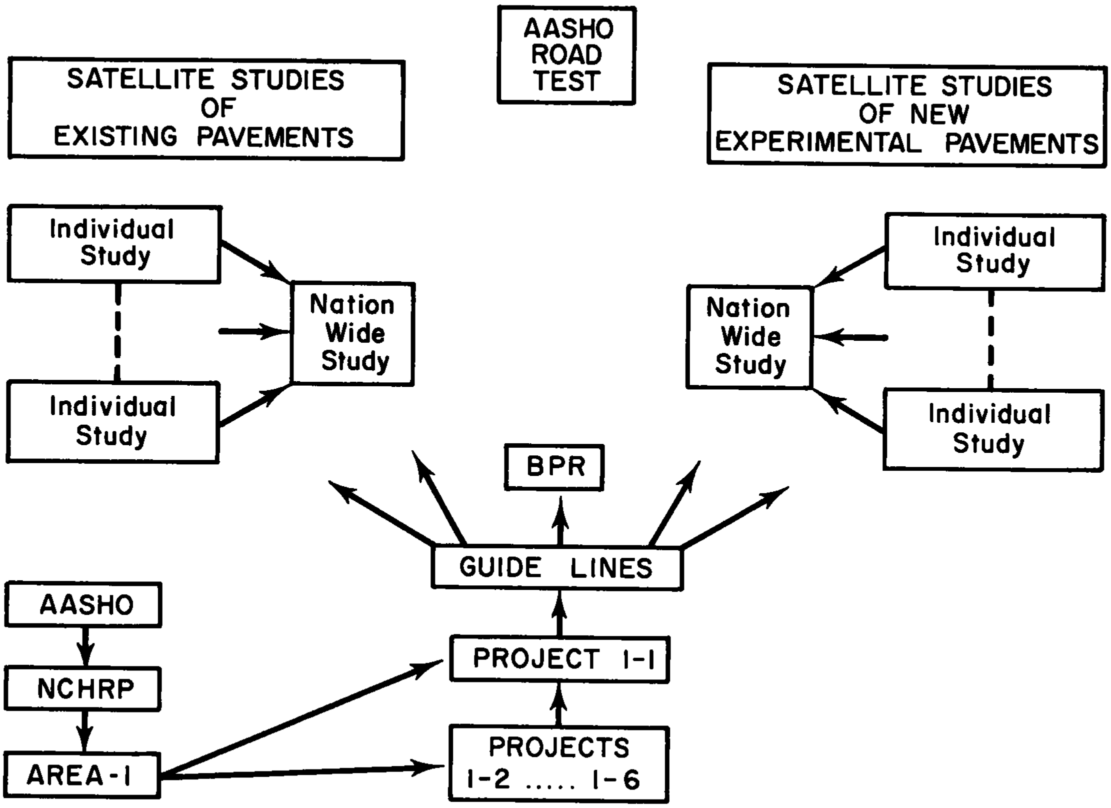

Figure 1. Pavement performance studies.

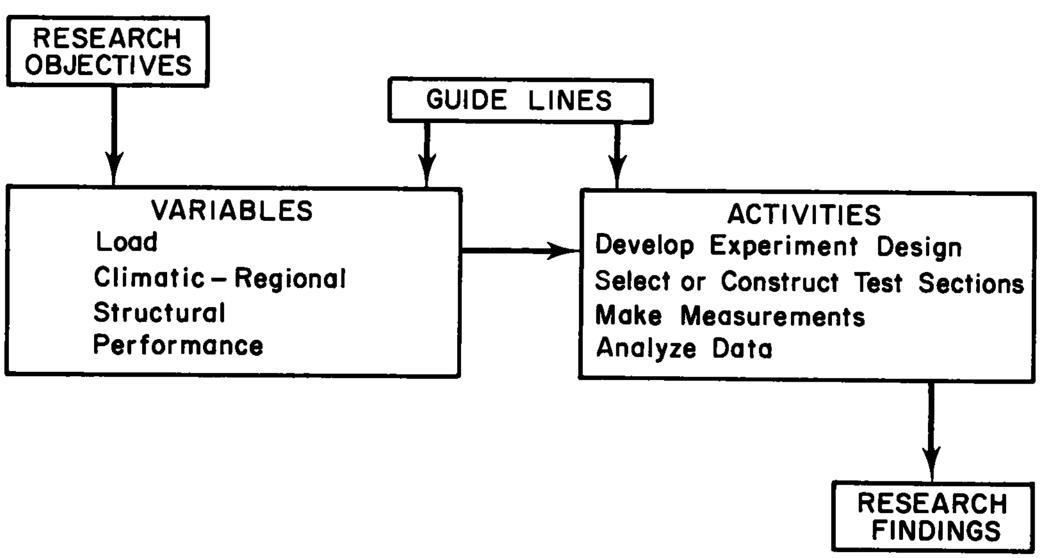

Figure 2. Aspects of satellite studies.

deal mainly with variables and activities which are part of virtually all pavement performance studies.

Any variable in a satellite study is considered to be either a load variable, a climatic or regional variable, a structural variable, or a performance variable. The general objective for a study might be, for example, to learn how a particular structural variable is affected by a climatic variable, or how some performance variable is affected by combined changes in load, climatic, and structural variables.

Four interrelated activities are required to produce this kind of information. Appropriate experiment designs need to be developed, test sections selected or constructed, and appropriate measurements made, processed, and analyzed.

The NCHRP Project 1-1 guidelines and this summary report are written in terms of these four classes of variables and four types of activities.

STRUCTURAL VARIABLES

A schematic view of a satellite test section is shown in Figure 3. The pavement system is considered to consist of a roadbed upon which the pavement structure is comprised of subbase and/or base and surfacing courses.

Five types of structural variables are discussed in the guidelines. The first type denotes thicknesses of pavement components: h_1 for surfacing, h_2 for base, and h_3 for subbase courses.

The second type includes strength characteristics of the structural components, denoted by s_1 for surfacing courses, s_2 for base courses, s_3 for subbase courses, and s_4 for roadbed. These characteristics will generally reflect elastic moduli, deformation moduli, and ultimate strengths of the structural components.

The third type of structural variable considered in the guidelines includes classifications that are often more qualitative than quantitative in nature. These are denoted by c_1 for surfacing material (*e.g.*, whether reinforced or nonreinforced), c_2 for base material (*e.g.*, stabilized or unstabilized), c_3 for subbase material (*e.g.*, general quality of the subbase aggregate), and c_4 for roadbed material (*e.g.*, AASHO class).

Only a few structural variables were studied in the Road Test; thus, there are many opportunities for extending the Road Test findings through satellite studies.

Two other structural variables describe the overall pavement system rather than any particular component. One of these is called composite strength, S, in the guidelines. This variable is some measure of the pavement system response to a single load (usually in terms of deflections, strains, or pressures) and can serve at least two purposes. The other is to provide data for checking or formulating theories of pavement behavior. It has also been shown that data on S are useful for predicting pavement life. Taken together these two purposes can form a link between theoretical movements under single loads and observed performance under years of assorted loads.

The final structural variable that is used in the guidelines is a structural index, D, which reduces all structural variables except S to a single scale. The structural index is not observed but is computed by some formula derived from previous analyses. Other terms used for D are thickness index, structural number, and equivalent design. Test sections in the AASHO Road Test had a wide range of structural index values for both flexible and rigid pavements, but it remains to be seen whether the same formulations, or layer equivalencies, will be found when different materials and climates are encountered in the satellite studies.

LOAD VARIABLES

The guidelines consider only three variables (Fig. 4) that describe the axle loads carried by a pavement section. One of these is an index, ΣL, defined as the number of equivalent 18-kip single-axle load applications carried by the section up to the

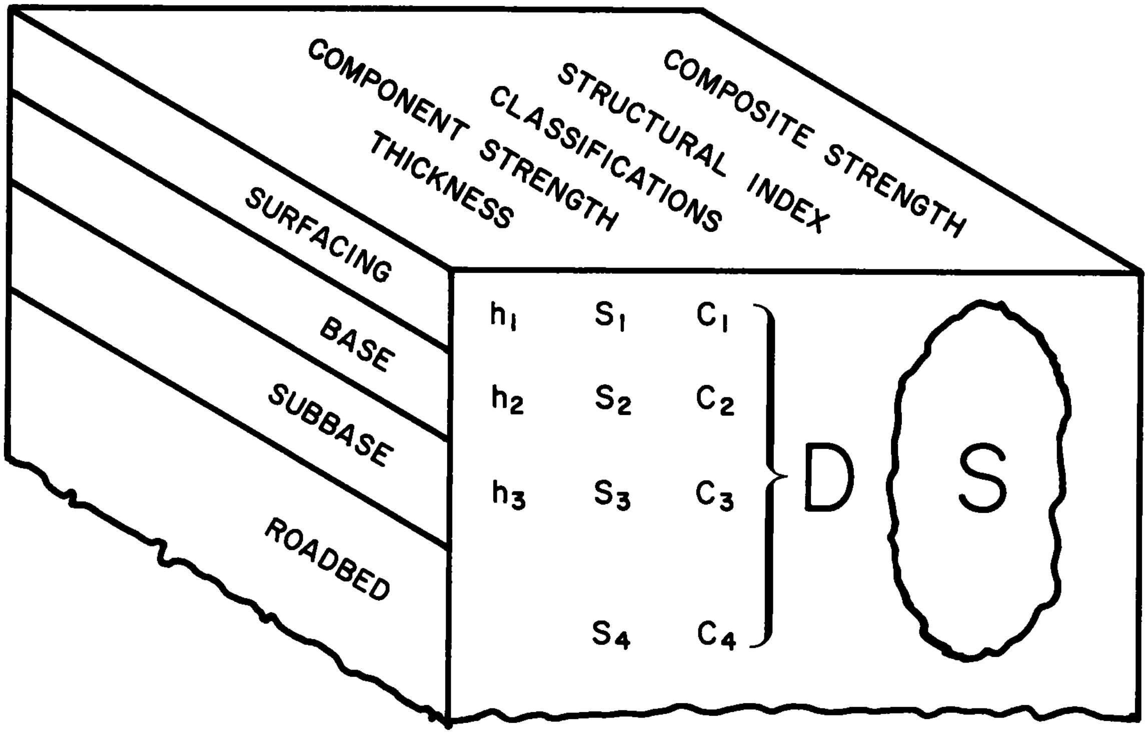

Figure 3. Structural variables.

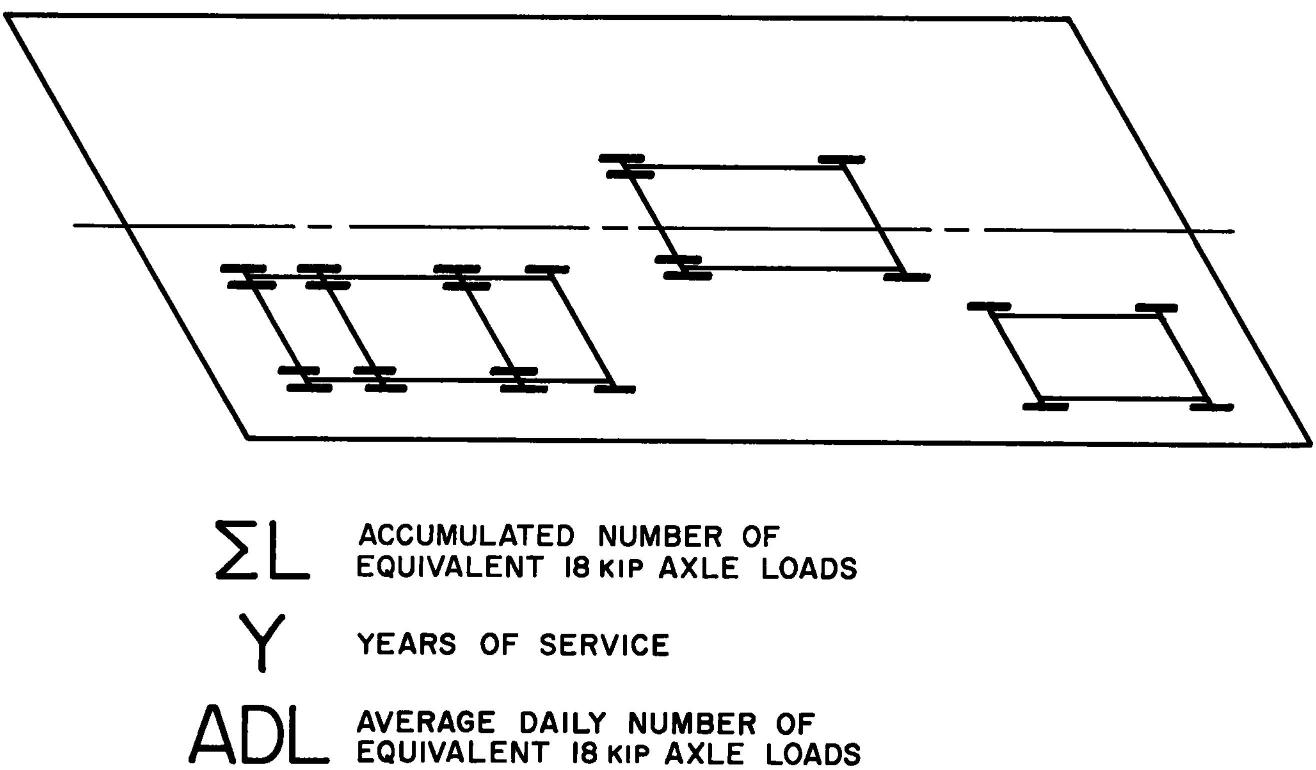

Figure 4. Load variables.

time of observation. The guidelines give load equivalency factors which were developed at the AASHO Road Test. When these are applied to suitable information on the load history of a test section, a value for ΣL can be estimated for any satellite test section.

For convenience, the number of years of service, Y, is included in the load variable category. A third load variable is considered in the guidelines, ADL, the average daily number of equivalent 18-kip axle-load applications.

One of the open questions at the end of the AASHO Road Test was whether the test sections would have performed differently had the axle-load applications been spread out over ten or twenty years instead of two. The satellite studies can be expected to yield answers to this important question.

CLIMATIC AND REGIONAL VARIABLES

Climatic and other regional variables represent one of the primary interests in the satellite studies. Although it is certain that these variables can affect pavement performance, it remains for the satellite studies to quantify their effects. It is of particular interest to determine how pavement structures used in the AASHO Road Test will perform in other regions of the country. As shown in Figure 5, climatic variables are denoted by v_1, v_2, . . ., and represent such variables as annual rainfall and depth of frost.

For certain purposes in the satellite studies it is sufficient to use a regional factor, RF, to differentiate among satellite test regions and the AASHO Road Test region. The regional factor is determined by analysis and indicates the extent to which pavement performance is better or worse in a given region than was observed at the AASHO Road Test for comparable conditions of load and initial structure.

Another regional variable discussed in the guidelines is, RS, the relative composite strength of comparable satellite and Road Test sections. It might be, for example, that long-term average deflections for comparable initial structures were only one-half as much in a particular satellite region as at the AASHO Road Test. In such a case the relative strength would be two for the region. Thus RS is measurable, unlike the regional factor, RF, which is dependent upon the outcome of analysis.

Climatic or regional variables may be considered as modifiers for certain structural variables, notably the as-constructed strengths of pavement components.

PERFORMANCE VARIABLES

The last class of variables (Fig. 6) includes perhaps four or five measures of surface deformation and deterioration, x_1, x_2, x_3, etc. These include distortion along the direction of travel (slope variance, roughness index, etc.), transverse distortions such as ruts, deteriorations such as cracking, and other undesirable surface features. Several of these variables can be weighted and combined into a present serviceability index, p. The initial value of p is denoted by p_0. Thus p_0 is calculated by formula from measurements in new pavement studies but must be estimated in studies of existing pavements.

As time and accumulated number of equivalent axle-load applications increase, it is expected that p will decrease from p_0, however slowly. At one or more points in time the serviceability index and accumulated load applications can be evaluated for any satellite test section. The graph of all such points is the section's performance record. Two illustrative performance records are shown in Figure 7, one for a pavement section whose performance is relatively low and one for a section whose performance is high.

A meaningful and simple statistic for any test section is its performance index, P, defined as the logarithm of the number of equivalent 18-kip axle-load applica-

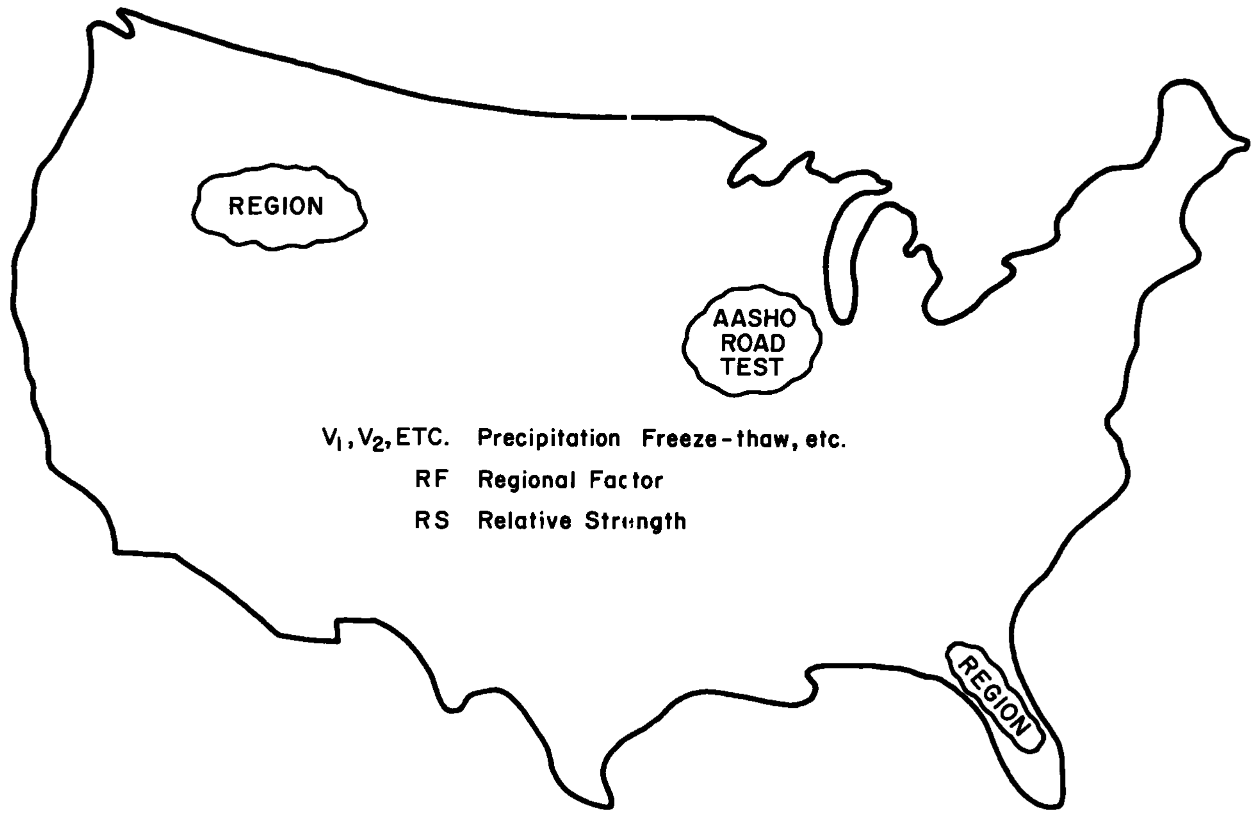

Figure 5. Climatic-regional variables.

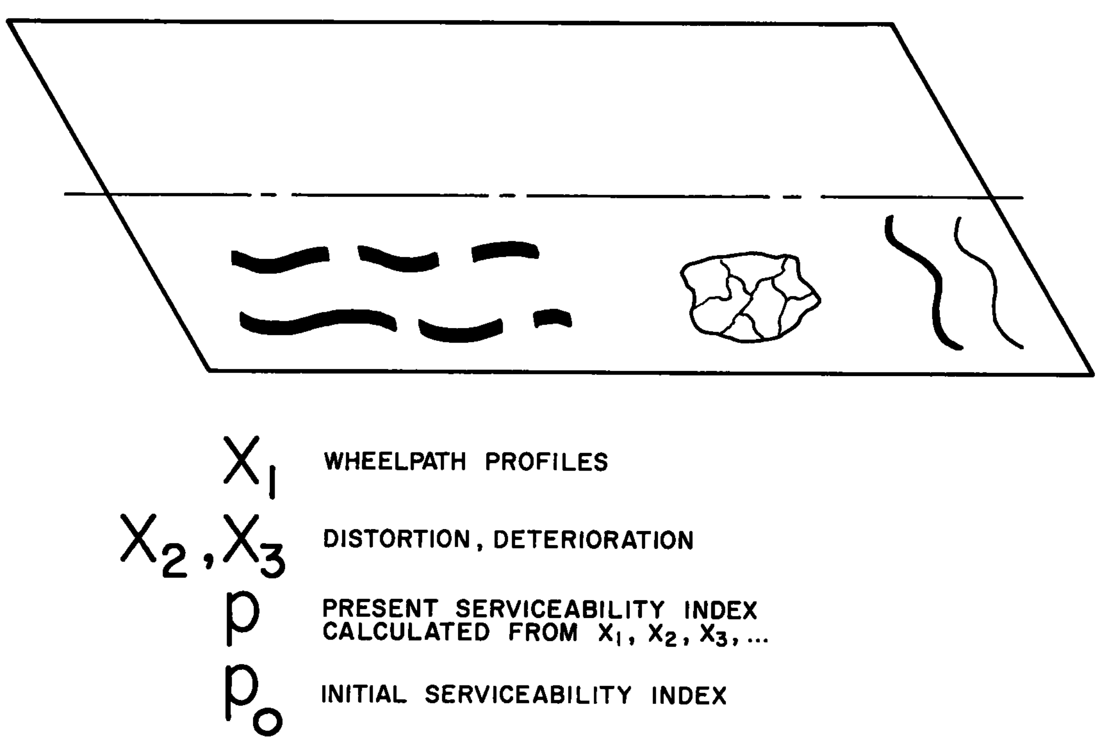

Figure 6. Performance variables.

tions experienced by the section when its serviceability index is $p = 2.5$. One section in Figure 7 reached serviceability level 2.5 after 100,000 equivalent applications and has a performance index $P = \log 10^5 = 5.0$. The other section experienced 10,000,000 applications and has $P = \log 10^7 = 7.0$. On this basis, AASHO Road Test sections had performance indexes ranging from about 3.0 to about 7.0. It is doubtful if any highway section will have a performance index as large as $P = 8.0$ because this would correspond to about 50 years of Loop 4 operation at the AASHO Road Test (around 1,000 18-kip axles per day).

MEASUREMENT OF VARIABLES

Now that the variables in a satellite study have been identified, at least in general terms (Fig. 8), the four major activities of a satellite study can be described. It is convenient to consider first the measurement of variables.

The guidelines contain much discussion and many recommendations for the measurement of structural, load, climatic or regional, and performance variables. It is recognized that the sponsors of various satellite projects will specify measurement programs which range from minimal to comprehensive measurements of many variables, depending upon the research objectives.

One of the basic proposals in the guidelines is that measurement teams be equipped and trained to obtain "common denominator" measurements on all satellite test sections, or at least on those which are part of a nationwide design. These teams would be supplemental to the sponsor's measurement programs and would visit each satellite project on a regular basis throughout the life of the project.

It is assumed in the guidelines that a manual specifying in detail how "common denominator" measurements are to be obtained will be developed for use by the measurement teams.

Whether undertaken by the measurement team, project sponsor, or both, the following measurement program is considered to be minimal for any satellite test section:

1. *Structural Variables.* Thicknesses of surfacing, base, and/or subbase courses; strength characteristics of each structural component, by at least one and preferably two test procedures; measurements for classification of structural components (wherever appropriate); and at least one measure of composite strength.
2. *Load Variables.* At least one loadometer study which applies directly to the test sections in the study. Load studies will ordinarily be supplemented by vehicle count studies and applicable trends of traffic composition.
3. *Climatic and Regional Variables.* Measurements to describe year-round test section climate and environment, as well as seasonal variations in composite strength, for example, "highs and lows" for deflections.
4. *Performance Variables.* Yearly evaluations of surface deformation and deterioration, present serviceability index and performance index. The guidelines give details for several alternative methods of obtaining present serviceability and performance index values.

DEVELOPMENT OF EXPERIMENT DESIGNS

The controlling activity in any satellite study is the development of an experiment design which shows how selected structural, load, and climatic or regional factors will be varied in combination with one another.

Test Site Factors

Certain variables will not vary appreciably within test sites but will have different levels from one test site to another. Such variables are called test site factors, and

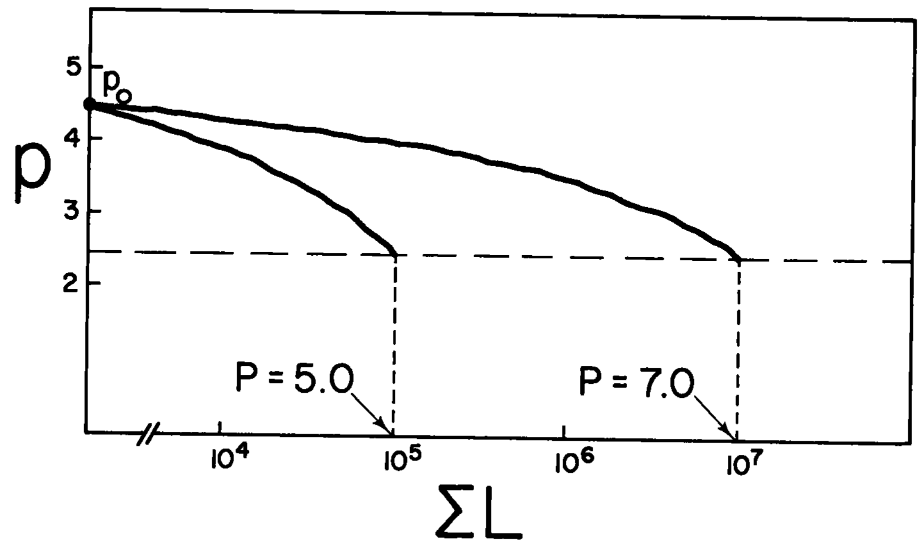

Figure 7. Performance records and performance indexes.

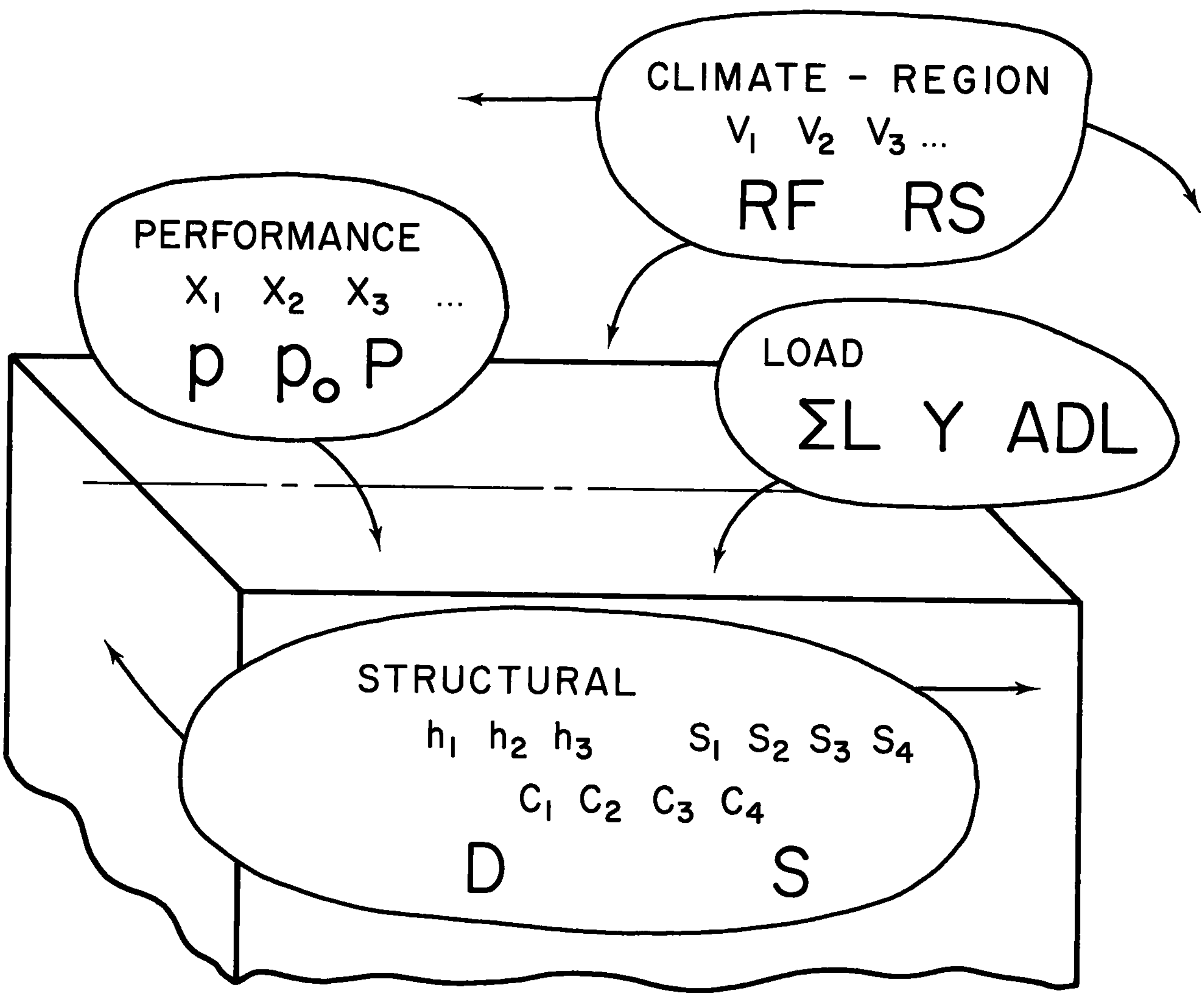

Figure 8. Variables in satellite studies.

will generally involve differences in roadbed material, climatic conditions, or rate of equivalent 18-kip axle-load accumulation.

A simple example is shown in Figure 9. Rainfall and freeze-thaw conditions, for instance, have been used to describe three levels of climatic severity: low, medium and high. The vertical scale shows three levels of as-constructed roadbed strength, perhaps in terms of subgrade modulus of reaction. Thus there are nine combinations of test site factors in the illustrative experiment design. It will be supposed in this example that all nine test site conditions will involve an ADL of around 500 equivalent 18-kip axle loads per day, so that ADL is not an experimental factor.

Pavement Structure Factors

The next question is whether any pavement structure factors will be included in the experiment design. If not, the example will be a two-factor study which has either the same pavement design at all nine test sites, or perhaps the same range of designs at every site.

It will be supposed that this example is a rigid pavement study and that two pavement structure factors will be varied at each test site. The first factor will be thickness of surfacing at two levels, seven and nine inches. It is assumed that the surfacing material, reinforcement and jointing is similar to that of the reinforced AASHO Road Test sections. The second pavement factor will be the strength of subbase material which is six inches thick for all test sections. The low-level strength is assumed to be equivalent to that of AASHO Road Test subbase, and a high-level strength will be obtained by cement stabilization. As shown in Figure 10, the illustrative experiment design provides for four different pavement designs at any test site, 7L, 7H, 9L, and 9H.

Complete Factorial Experiments for Individual Satellite Studies

If the experiment design contains all possible combinations of selected factor levels, the study is a complete factorial experiment. For the example, Figure 11 shows 36 test sections in the complete factorial, nine test sites in all combinations with four pavement structures. The guidelines recommend this type of experiment design for any individual satellite study, using either two, three, or four factors and either two or three levels for any factor. It is also recommended that at least one factor be similar to a Road Test factor and that one or more new factors be included. Furthermore, it is proposed that at least one level of any factor should correspond to a level that was used in the Road Test. Of the four factors in the example, only the surfacing thickness factor was varied at the AASHO Road Test, so this study will provide information on three new factors.

Experiment Designs with Factors Confounded

In existing pavement studies, particularly, it may not be possible to fill all cells in a proposed experiment design. As an extreme case, perhaps only the seven sections shown in Figure 12 can be found in the existing highway system. It can be seen that the stronger pavement designs are associated with more adverse roadbed and climatic conditions and that weaker designs are found in more favorable roadbed-climatic conditions. This situation is to be expected in existing pavement studies since the basic principles of pavement design imply that such compensations be made. As the example now stands, a few direct comparisons can be made, but for the most part surfacing and subbase effects are confused or confounded with

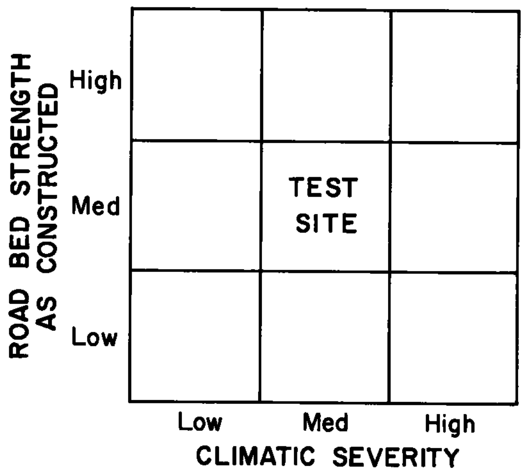

Figure 9. Experiment design for test site factors.

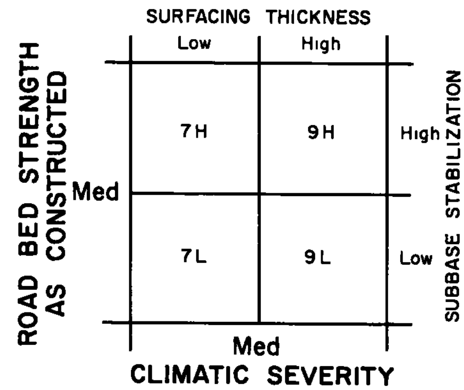

Figure 10. Experiment design for pavement structure factors.

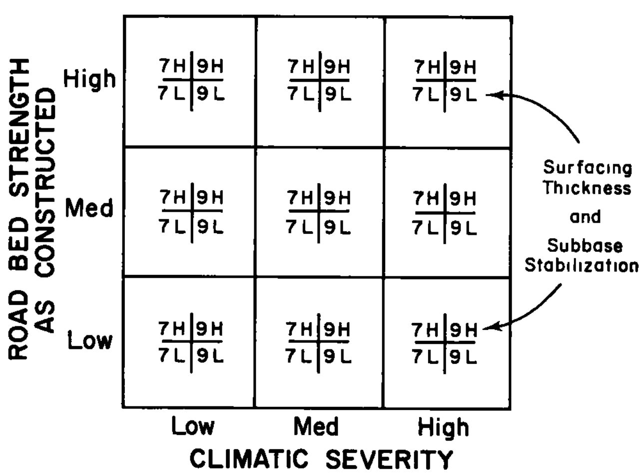

Figure 11. Complete factorial experiment—36 test sections.

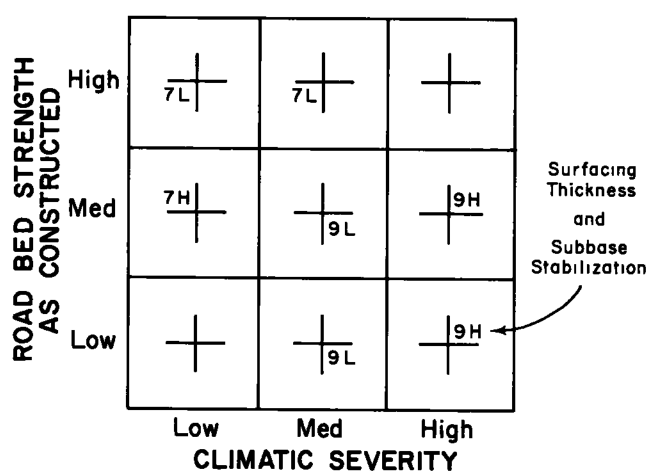

Figure 12. Design with factors confounded—7 test sections.

each other and with the effects of test site factors. Still further confusion would occur if ADL were to vary from one site to another. In this example it is virtually impossible to analyze the separate effects of the four factors selected for study. If the research objectives definitely include the study of all four variables, then consideration will have to be given to the construction of new experimental sections to give a complete factorial experiment.

Composite Experiment Designs for Nationwide Satellite Studies

In addition to experiment design guides for individual satellite studies, the guidelines include composite experiment designs that can be used for nationwide cooperative studies of pavement performance. The present illustration shows the nature of the proposed nationwide designs. Three types of test sites are shown in Figure 13: four factorial sites involving the high and low levels of roadbed strength and climatic severity, one centroid site with medium levels, and four extension sites which introduce very high and very low levels of one factor when at the medium level of the other factor. In the nationwide composite design, five test site factors are used: two for roadbed strength, two for climatic conditions, and one for daily load rate, with a total of 32 factorial sites, one centroid site, and ten extension sites. Thus a nationwide composite experiment would involve 43 test sites encompassing a wide range of roadbed and climatic conditions.

As shown in Figure 14, several additional combinations of surfacing thickness and subbase stabilizations are introduced for the composite experiment design. One of these is for a centroid structure which has eight-inch surfacing thickness and medium stabilization level. This 8M section occurs once at the centroid site, once at every factorial site, and in duplicate at all extension sites. Thus the centroid structure is common to all test sites and serves as a control or standard section. Factorial sites now include only two of the four pavement designs which were in the complete factorial experiment of Figure 11, but these have been selected according to certain mathematical principles.

At the centroid site extra low and extra high levels of surfacing thickness (six and ten inches) are used with medium stabilization, and extra low and extra high levels of subbase stabilization (VL and VH) are used with medium surface thickness. Thus the centroid site now has five test sections for the study of wide variations in pavement structure factors.

In the illustrative composite experiment design, only 25 test sections are used to study the same factors, and over wider ranges, as for the 36-section complete factorial experiment. The nationwide designs given in the guidelines involve six structural factors in addition to the five test site factors previously described. Each of the ten extension sites has two centroid sections, each of the 32 factorial sites has five sections, and the centroid site has 13 sections, totaling 193 test sections for any pavement type under study. To study eleven factors in a complete factorial experiment would require over 2,000 test sections. The composite experiment design is believed to be near optimum for nationwide cooperative studies. Any cooperating state might have two, five, or more sections in the overall pattern, provided that appropriate test site conditions are available.

In some cases, test sections representing a part of a nationwide experiment design might also be part of an individual study.

SELECTION OR CONSTRUCTION OF TEST SECTIONS

After an experiment design has been developed for selected factors, specifications are needed for all structural, load, and climatic or regional variables not covered by the experiment design. Such specifications relate to test section dimensions,

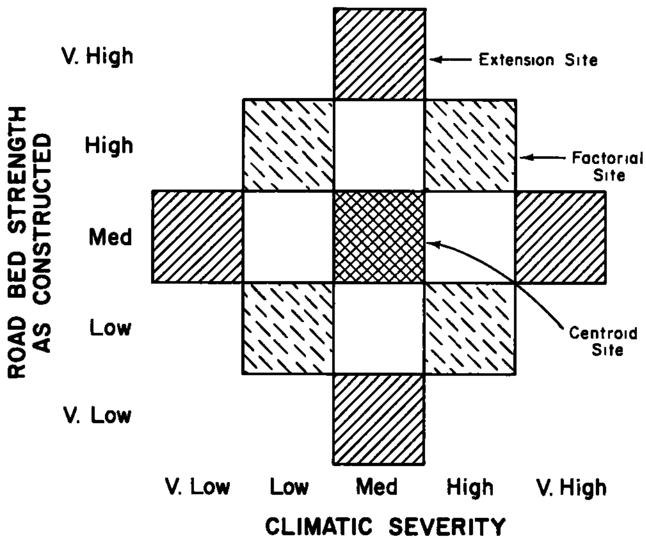

Figure 13. Composite experiment design—test sites.

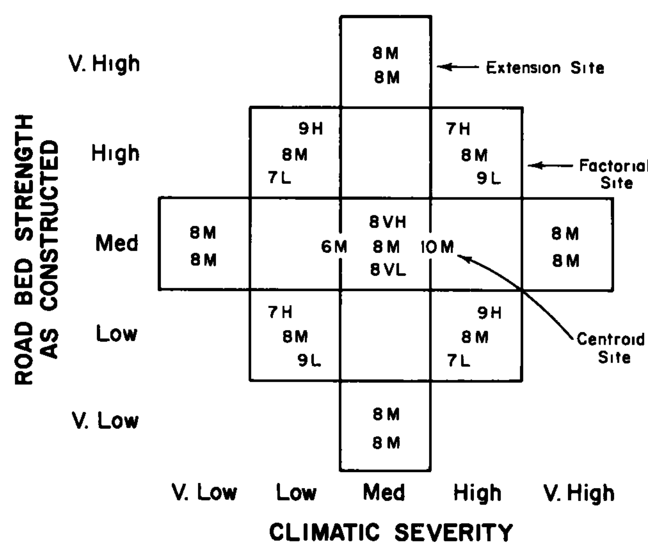

Figure 14. Composite experiment design—25 test sections.

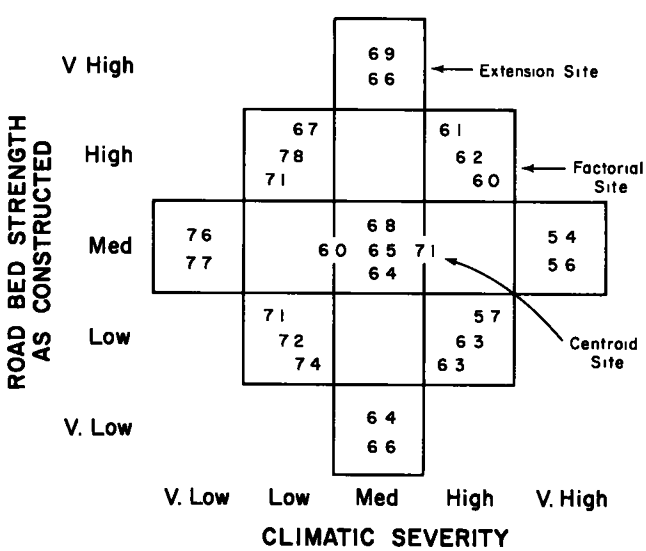

Figure 15. Performance index data.

provision for destructive testing, ground rules for the immediate environment of test sections, and values or permissible variations for materials and construction procedures. Many of these items are discussed in the guidelines but all details are left to the sponsors of individual or nationwide satellite projects.

Preliminary data on sections selected for existing pavement studies may reveal the need for revisions in the experiment design. As a general rule it is suggested that if suitable test sections, including sufficiently precise load histories, cannot be found for at least 90 percent of the planned experiment design cells, then the design should be reduced through the deletion of factors and factor levels. It is especially important in existing pavement studies to select sections in such a way that variables occurring in the experiment design are not correlated with other variables. In the guidelines, special techniques are given for handling this problem.

ANALYSIS OF MEASUREMENTS

The final activity in a satellite study is the analysis of measurements to obtain the information implied by the objectives of the study. For studies of new experimental pavements it is expected that from five to ten years of traffic will be required before performance data will be sufficient to give meaningful data analyses. In the meantime, of course, it will be possible to make analyses of composite strength.

Without limiting the type or number of analyses which can be made from satellite research data, the guidelines propose that the observations be used in at least five types of analysis. Many details for these analyses are described and illustrated in the guidelines, and are now summarized with respect to the composite experiment design of Figure 14.

Performance Classification of Test Sections

The first analysis suggested in any satellite study is essentially the classification or ranking of test sections with respect to performance index values. The performance index values should make it apparent as to whether some pavement designs are better performers than others in a given region, and which designs, if any, are not really adequate. For example, the uppermost section in Figure 15 has a performance index of 6.9, that is, nearly $10^7 = 10{,}000{,}000$ equivalent axle loads were survived before the section's present serviceability was $p = 2.5$. This corresponds to two years of the heaviest loads (Loop 6) in the AASHO Road Test. Three sections in Figure 15 have P less than 6.0 and reached serviceability level $p = 2.5$ before three years of the project were completed. Eight sections have P from 6.0 to 6.5 and are predicted to have $p = 2.5$ before 15 years of service, and the remaining 14 performance indexes are 6.5 or over. Most of these sections are not expected to reach $p = 2.5$ for well over 30 years under present loading conditions. For the more favorable roadbed strength and climatic conditions, the results of this study indicate which pavement designs are adequate. For the more adverse conditions, it is clear that stronger designs are needed than were used in the experimental study. Tentative conclusions of this type can be drawn simply by scanning the performance index values of the test sections.

Direct Comparison with AASHO Road Test Performance

The guidelines include performance index values for every AASHO Road Test section so that direct comparisons can be made between performance indexes of satellite and AASHO Road Test sections as shown in Figure 16. It is recommended that such contrasts be made for all comparable sections. In the present example it is supposed that three test sections have the same roadbed, subbase, and climatic

SURFACE THICKNESS AND SUBBASE STABILIZATION	SATELLITE SECTIONS WITH AASHO ROADBED AND CLIMATE	AASHO ROAD TEST SECTIONS
6.0 Low	P = 6.0	
6.5 Low		AVG P = 6.0
8.0 Low	P = 6.6	AVG P = 6.4
9.5 Low		AVG. P = 7.0
10.0 Low	P = 7.1	

Figure 16. Direct comparisons of performance indexes.

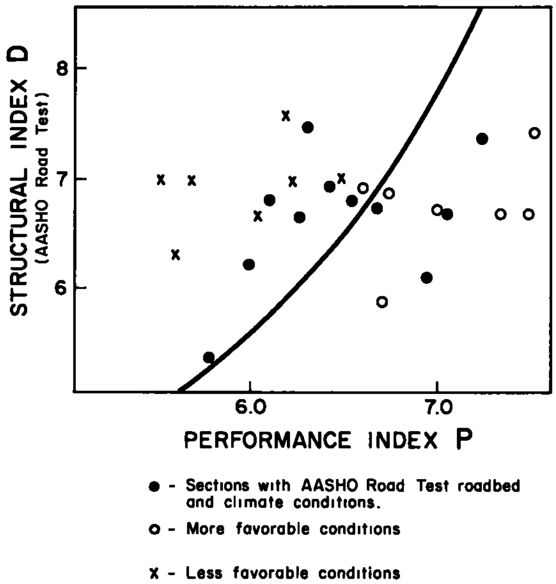

Figure 17. Satellite performance vs AASHO Road Test equation.

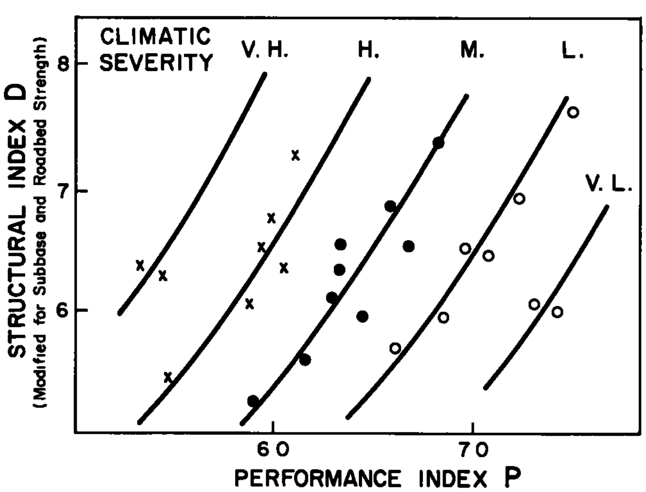

Figure 18. Modified performance equation.

conditions as at the Road Test. Comparisons can be made between the performance indexes of these sections and corresponding indexes for reinforced AASHO Road Test sections with similar surface thicknesses. If, as in Figure 16, the direct comparisons are in close agreement, there is reason to believe that adjustment of the AASHO Road Test findings to the satellite test results will involve only the new factors introduced into the satellite experiment design. If the direct comparisons are not favorable, as may be the case in a number of satellite studies, it might be that the roadbed strength, climatic classification, construction procedures, or other factors were not really comparable with AASHO Road Test sections.

Performance Relationships with Structural, Load, and Climatic or Regional Variables

One analysis recommended for satellite studies is the adjustment or development of performance equations to fit the satellite test data. Performance data at the AASHO Road Test were analyzed to give so-called performance equations showing the number of axle load applications which might be expected from a particular pavement design before the pavement had a specified serviceability index. These equations necessarily involved only structural factors which were varied in the Road Test experiment designs. In fact, the reported equations involved only surfacing, base, and subbase thickness for flexible pavements and only surfacing thickness for rigid pavements.

Figure 17 shows the graph of a rigid pavement performance equation developed from the AASHO Road Test data, in terms of structural index versus performance index. Solid points in the graph represent eleven test sections in the present illustration whose roadbed-climatic conditions are presumed to be fairly similar to those at the AASHO Road Test. It can be seen that the performance of these particular sections agrees in general with the AASHO Road Test performance equation. Performance of the remaining satellite sections, however, does not agree with the Road Test equation. Thus the equation needs to be extended to the conditions encountered in the satellite study.

The guidelines give details and illustrations for a number of alternative procedures for developing performance equations. When one of these procedures is applied to the illustrative data a new performance equation is obtained. The graph of the new equation, shown in Figure 18, gives a different curve for each region of the satellite study and involves a structural index which accounts for the different subbase and roadbed strengths that were used in the study. Thus the AASHO Road Test equation has been extended to fit conditions that were not present in the Road Test itself. If the curves were actual instead of hypothetical, they would presumably be useful for determining appropriate pavement designs for specified performance requirements.

In an individual study there may only be enough information to extend certain parts of the equation, for such aspects as the effect of roadbed material or climate. Data from the nationwide studies, however, should make it possible to check (or modify) all effects observed at the Road Test as well as to extend the equations to a wide range of structural and climatic conditions.

Performance Relationships with Measures of Composite Strength

Another type of analysis can be illustrated with hypothetical Benkelman beam deflections as shown in Figure 19. Assuming that these are indicators of the composite strength, S, of the pavement structures under specified loading and temperature conditions, a relationship can be developed between S and P. For

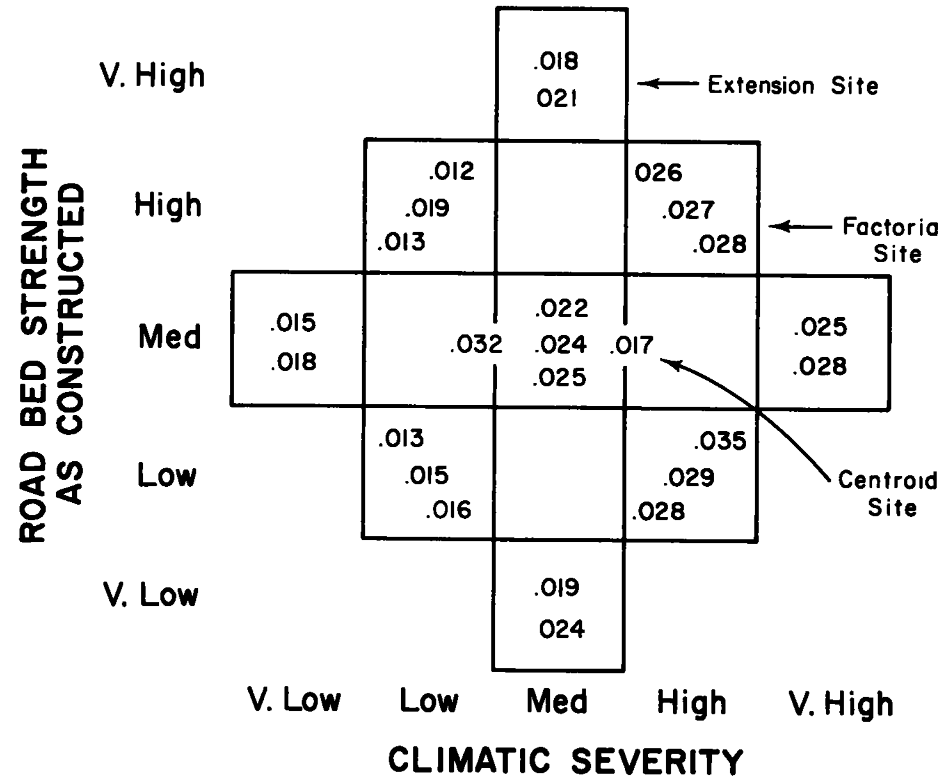

Figure 19. Composite strength—slab edge deflection data.

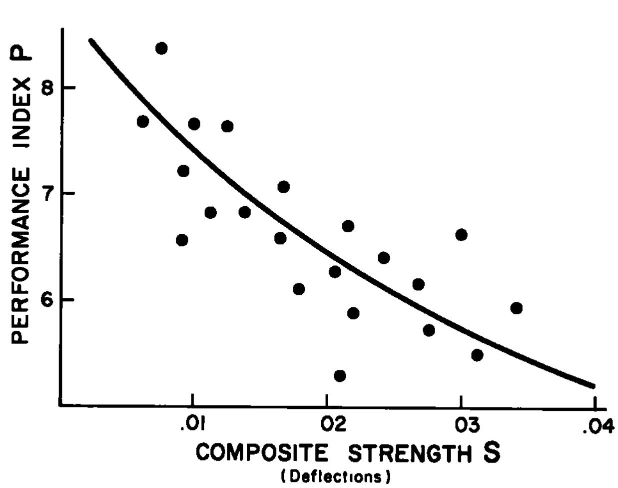

Figure 20. Performance index vs slab edge deflections.

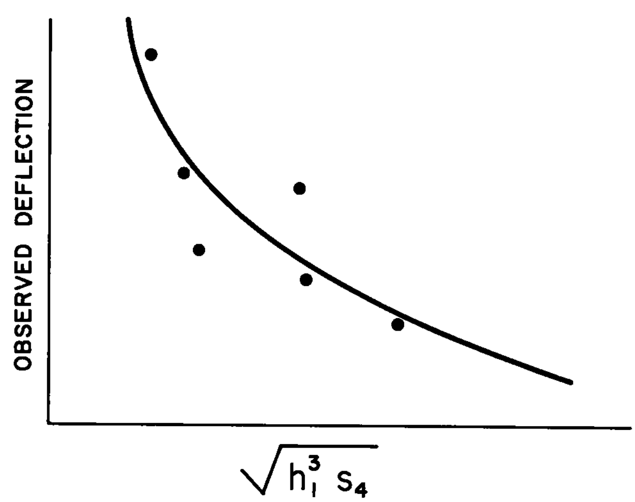

Figure 21. Westergaard deflection theory.

the illustrative data one such relationship turns out as shown in Figure 20. The scatter about this curve is somewhat larger than for the relationship of performance to structural factors. To the degree, however, that such an equation gives satisfactory predictions of performance it can be used to estimate the "life" of an existing pavement structure.

Testing of Structural Theories

Another type of analysis, discussed but not illustrated in the guidelines, involves the comparison of satellite test observations with corresponding values given by existing theories of pavement behavior. It may be of interest to determine the degree to which the illustrative deflections concur with, for example, the Westergaard theory of deflection. This particular theory says that deflections are inversely proportional to the three-halves power of surfacing thickness and to the one-half power of the roadbed modulus of reaction. Figure 21 shows that deflections at three sites with medium climatic severity are in fairly close agreement with the Westergaard relationship indicated by the curve.

It is supposed that such studies will represent the primary interest of theoretically-minded investigators in the satellite program, but it is presumed that any theory must find its practical application in satisfactory predictions of long-term pavement performance over wide ranges of many variables. Since at the present time no theories exist for relating composite strength to overall pavement performance, such relationships must be developed on an intuitive basis.

It is emphasized in the guidelines that there are many alternative procedures for analysis of satellite test data, and that different types of analysis should be explored in the search for the most useful and meaningful relationships.

CONCLUDING REMARKS

In summary, the NCHRP Project 1-1 guidelines have been developed for pavement performance studies for existing pavements and for new experimental pavements.

The guidelines utilize much of the information obtained at the AASHO Road Test, and are written in terms of four classes of variables: performance, structural, load, and climatic or regional. Four major activities are discussed in detail: the development of experiment designs, the selection or construction of test sections, the measurement of variables, and certain types of data analysis.

The effects of some variables on performance were studied at the AASHO Road Test, but the effects of other variables will necessarily be determined only through individual and nationwide satellite studies.

Many details of satellite study activities must be left to the various sponsors. To a large extent the guidelines contain guides rather than "recipes" for the conduct of any particular project, and implementation of satellite research will involve quite specific choices and decisions which were considered to be beyond the scope of the guidelines. The guidelines do, however, provide specific bases and recommendations for the coordination of satellite studies with one another and with the AASHO Road Test study of pavement performance.

THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The Academy itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the Academy and the government, although the Academy is not a governmental agency.

The National Research Council was established by the Academy in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the Academy in service to the nation, to society, and to science at home and abroad. Members of the National Research Council receive their appointments from the president of the Academy. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the Academy and its Research Council thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The Highway Research Board was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the National Research Council. The Board is a cooperative organization of the highway technologists of America operating under the auspices of the Academy-Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.