A SYSTEMS ANALYSIS OF RIGID PAVEMENT DESIGN

by

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PREFACE

This report presents a conceptual rigid pavement design system and a design procedure in the form of a computer program called RPS1 for "Rigid Pavement System One." Several relationships are developed and combined with existing models to analyze and design rigid pavements as a system based on economics.

The report is also meant to be a background document for further work to be done in improving the working systems model within the guidelines of the conceptual system described.

This is the fifth in a series of reports that describe the work done in the project entitled "A System Analysis of Pavement Design and Research Implementation." The project proposed a long range comprehensive research program to develop a systems analysis of pavement design and management. The project is supported by the Texas Highway Department in cooperation with the Federal Highway Administration Department of Transportation.

The computer program presented here is written for the CDC 6600 computer. It is in FORTRAN language and only minor changes are required to make it compatible with the IBM system. Duplicate copies of the program deck and data cards for the example problem may be obtained from the Center for Highway Research, The University of Texas at Austin.

Mr. F. H. Scrivner is thanked for writing several concepts used in this system which were evolved by him during the development of flexible pavement system reported in 1969. The cooperation of the entire staff of the Center for Highway Research of The University of Texas at Austin is appreciated. Thanks are due to Miss Darlene Neva, Mrs. Rose Mary Sturges, and Mrs. Jean Merritt for typing the drafts of the report and to Mr. Arthur Frakes for his assistance with the manuscript. The help of Mrs. Nancy Braun for her assistance in computer programming is greatly appreciated.

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LIST OF REPORTS

Report No. 123-1, "A Systems Approach Applied to Pavement Design and Research," by W. Ronald Hudson, B. Frank McCullough, F. H. Scrivner, and James L. Brown, describes a long-range comprehensive research program to develop a pavement systems analysis and presents a working systems model for the design of flexible pavements.

Report No. 123-2, "A Recommended Texas Highway Department Pavement Design System Users Manual," by James L. Brown, Larry J. Buttler, and Hugo E. Orellana, is a manual of instructions to Texas Highway Department personnel for obtaining and processing data for flexible pavement design system.

Report No. 123-3, "Characterization of the Swelling Clay Parameter Used in the Pavement Design System," by Arthur W. Witt, III, and B. Frank McCullough, describes the results of a study of the swelling clay parameter used in pavement design system.

Report No. 123-4, "Developing A Pavement Feedback Data System," by R. C. G. Haas, describes the initial planning and development of a pavement feedback data system.

Report No. 123-5, "A Systems Analysis of Rigid Pavement Design," by Ramesh K. Kher, W. Ronald Hudson, and B. Frank McCullough, describes the development of a working systems model for the design of rigid pavements.

ABSTRACT

Design of portland cement concrete pavements is a complex procedure involving the evaluation and analysis of numerous variables. A wide variety of variables within the broad categories of loads, environments, material properties, maintenance, progressive failure, and economics must be considered in an ideal design procedure. Concrete pavement and overlay types, reinforcement selection, joint detailing, and selection of subbase materials are other factors increasing the complexity of design.

Various methods of design have been presented in the past, but no procedure is generally acceptable due to the limited nature of the problem and analysis. The wide variety of structural and economic factors demands that a procedure be evolved to analyze various parts in a coordinated effort called systems analysis.

A conceptual rigid pavement system is presented which formalizes the myriad of intertwined variables into a series of mathematical models. A method is developed in the form of a computer program to solve various models, some developed as part of this work and others adopted from the state-of-the-art. The program utilizes about 115 different input variables and analyzes numerous possible solutions generated within the boundaries defined by constraints. Output is a set of pavement design strategies based on increasing value of present worth of overall costs. Details with respect to selection of thicknesses, materials, reinforcements, and joints as well as overlay patterns and predicted lives are presented for each design.

A small sensitivity analysis of the developed system is also presented in order to create confidence in the reasonableness of the system and its output.

KEY WORDS: rigid pavements, pavement design, pavements, systems analysis, systems engineering, optimization, computer program, performance.

SUMMARY

A procedure has been developed in the form of a computer program, RPS1, to design rigid pavements in a systematic framework. The program utilizes about 115 different input variables. All possible solutions to the problem within the limits specified by the designer are analyzed. Each design strategy is based on the analysis of details such as thicknesses, materials, reinforcements, joints, and overlay patterns. Initial and future costs incurred are calculated for each strategy and output is a best set of alternate designs to choose from based on the present worth of total overall cost. The design procedure is thus an aid to the administrator in exploring design options with no loss of decision-making power.

The computer program is one of the software subsystems developed for an overall systematic pavement design and research program. The development, in addition to providing the immediate benefits of present knowledge, has also pointed out areas of further modifications for continual improvement of the design system, and this needed research is reported.

IMPLEMENTATION STATEMENT

The rigid pavement system described in this report for the design of concrete pavements utilizes concepts and models which are already under trial implementation by the Texas Highway Department. The method of design therefore can be implemented with a small effort and no organizational change. A relatively comfortable and confident transition to this computer-oriented design procedure can be expected.

The program can be used in a district pavement design function through the Automation Division computer. Pavement design offices can obtain inputs from Materials and Tests, Planning Survey, and Automation Divisions. The district office can furnish data on maintenance, cost inputs, material availability information, and test results. The feasible design alternates shown in the computer output will be presented to the district administration for design selection for inclusion in plans, specifications, and estimates.

The rigid pavement system will be introduced on a gradual basis as time and personnel are available. A few districts will be involved initially, and as interest in the system develops, its use will increase.

The pavement design procedure has the potential benefit of obtaining the design in one computational step and solving the design problem more capably by using the best of the existing state-of-the-art methods. It is a definite technical improvement over the simple hand computational methods already in use. The computer program considers many more design options than presently considered and provides the administrator with several options to choose from in a concise output. The procedure, therefore, saves calendar time through reduction of correspondence, reduces manhours used for going through design options, eliminates errors inherent in the current simplified hand computational procedures, and provides advanced technology to be used for rigid pavement design.

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PARTIAL LIST OF SYMBOLS

Symbol	Definition
a	Radius of a circle equal in area to the loaded area
A_p	Length of analysis period
α	Standard deviation for a variable
b	Swelling clay parameter
b_c	Swelling clay parameter for the new performance period
b_p	Swelling clay parameter for previous performance period
β	A positive power for the serviceability trend curve
β_{18}	A positive power for 18-kip single-axle loads
C_a	Class 2 and sealed cracks
C_c	Cost of in-place concrete
C_F	A correction factor
C_i	Initial cost of a design
C_j	Cost of joints
C_n	Cost of traffic delay during nth overlay, per square yard of pavement
C_o	Present worth of the total cost of providing overlays
C_p	Present value of a cost
C_r	Cost of reinforcement
C_s	Cost of in-place subbase
C_t	Total cost

Symbol	Definition
C_D	Coefficient of deteriorated concrete slab
C_{mt}	Present worth of the total cost of maintenance
C_{oc}	Present worth of the total cost of all overlays (materials and construction)
C_{od}	Present worth of the total cost of all overlays (traffic delay during overlay operations)
C_{pf}	Present value of all future costs of a strategy
C_{sc}	Present worth of the cost of all seal coats
C_{sp}	Cost of subgrade preparation
C_{one}	Cost of providing one seal coat, per square yard of pavement
C_{sal}	Present value of salvage returns
C_f	A cost in future
D	Concrete thickness
DT	Thickness design term (= D + 1)
D_1	Thickness of asphalt concrete overlay
D_2	Thickness of concrete slab
D_3	Thickness of subbase
D_{fd}	Directional distribution factor
D_{fl}	Lane distribution factor
DT_m	Modified thickness design term
E	Modulus of elasticity of the concrete
E_1	Modulus of elasticity of asphalt concrete
E_2	Modulus of elasticity of concrete

Symbol	Definition
E_3	Resilient modulus of subbase material
E_4	Resilient modulus of subgrade
E_f	Erodability factor
E_i	Equivalence factor for load i
E_s	Modulus of deformation of subgrade material
E_{ic}	Computed equivalence factor for ith axle load
f_c	Allowable flexural stress in concrete
f_s	Allowable tensile stress in steel
F_a	Average coefficient of friction
G	$\log \frac{P_1 - p}{P_1 - p_L}$
G_{fa}	Axle growth rate
G_F	ADT growth factor
h_e	Thickness of existing concrete slab
h_o	Thickness of continuous concrete overlay
H	Thickness of elastic isotropic subgrade
I_r	Interest rate
J	Load transfer characteristic coefficient
k	Modulus of support reaction
K_M	Modified value of K_T
K_T	Value of k at the top of subbase
ℓ	Radius of relative stiffness

Symbol	Definition
L	Tire load
L_1	Axle weight
L_2	Axle code
L_d	Slab dimension, longitudinal
L_1'	Lower value of a load range
L_2'	Upper value of a load range
L_i'	Average value of a load range
M_R	Subgrade resilient modulus
μ	Poisson's ratio for concrete
μ_s	Poisson's ratio for subgrade material
p	Serviceability trend value at any time
p_L	Serviceability index at which a section was "out of test"
P	Serviceability trend value at any time due to swelling clay only
PSI	Present Serviceability Index
P_1	Initial serviceability index
P_2	Terminal serviceability index
P_a	Patched area
P_p	Ultimate value of serviceability index due to swelling clay
P_{sv}	Percent salvage value
ϕ	Serviceability loss function at any time due to swelling clay
ϕ'	Total value of serviceability loss function at infinite time due to swelling clay

Symbol	Definition
q	Applied lateral load
ρ	Value of W when $p = p_L$
ρ_{18}	Value of W_{18} when $p = p_L$
$\overline{SV}$	Slope variance
S_b	Bending stiffness of the plate
S_x	Flexural strength of Road Test pavements
σ_{18}	Corner stress at Road Test due to 18-kip single-axle load
σ_c	Maximum tensile stress due to a corner load
σ_e	Maximum tensile stress due to an edge load
σ_i	Maximum tensile stress due to an interior load
σ_{cm}	Corner stress calculated by Spangler's equation and modified material properties
σ_{cs}	Corner stress calculated by Spangler's equation
t	Time in years
t_n	Time when nth overlay is provided
T_f	Time-traffic exposure factor
T_n	Thickness of nth overlay
T_s	Tensile strength of concrete
T_{TC}	Subgrade Texas triaxial class
V_c	Confidence level for a variable
V_d	Design value of a variable
V_m	Mean value of a variable

Symbol	Definition
w	Deflection at any point of the slab
w_c	Weight of concrete
W	Number of axle-load applications
W_{18}	Number of 18-kip single-axle load applications
W_{18m}	Modified number of 18-kip single-axle load applications
W_i	Number of applications of axle load i
W_t	Total equivalent 18-kip single-axle applications up to time t
W_{ic}	Counted number of axles in ith category
W_{AP}	Total equivalent 18-kip single-axle applications during the analysis period
W_{tot}	Total equivalent 18-kip single-axle applications
X_1	Age of pavement after initial or an overlay construction
X_2	Number of days when maximum daily temperature is below 32° F

CHAPTER 1. INTRODUCTION

Portland cement concrete or rigid pavement analysis is a complex soil-structure interaction problem and many empirical and semiempirical methods of design have been used since 1900. The empirical nature of the method has been due in part to the limited knowledge of materials behavior and failure mechanisms and in part to limitations of analytical techniques.

From time to time, the limited knowledge has been broadened by further theoretical analysis and observations on controlled field experiments, prototypes, and laboratory experiments. The research efforts have generally been oriented to cover a specific aspect of this subject, but unfortunately there has been a lack of coordination in developing an understanding among the various parts. As a result, these efforts have not improved the design procedures to a form general enough to be extrapolated for various materials and environmental conditions.

Most of the design procedures have been oriented toward the objective of obtaining a structurally successful thickness of concrete to survive the entire design life of the facility. Concrete thickness is an important aspect of the pavement but should not be the only design criterion. Pavement should be considered as an investment and analyzed using economic concepts. The combination of money and materials should be analyzed to achieve the best resource allocation.

A wide variety of interests demands that an effort be directed towards a fundamental understanding of vrious parts of the problem in a coordinated framework or system. The multitude of physical and social variables involved should be sorted out and related in meaningful ways using systems engineering concepts.

A comprehensive formulation of the rigid pavement design process utilizing the integration of technological and economic attributes will take a number of cycles of model formulation, implementation, and feedback. It will involve a large amount of research over a number of years. However, immediate payoffs can be obtained by coordinating the various areas of the existing state-of-the-art as the starting point for the broader framework of a comprehensive system.

Such an approach has led to the formulation of a working system called the rigid pavement system. This design method uses various models fitted together in a computer program. Available concepts dealing with various parts of the system are utilized. Certain models, which are pertinent to the coordination of the design method and for which existing concepts are inadequate, are mathematically developed using engineering judgments and statistical techniques.

At this stage of knowledge, it is difficult to quantify the relative importance which the decision maker should ascribe to various economic, social, and experience values. The output, therefore, is arranged to present the designer and the decision maker with an ordered choice. A large variety of pavement design options are investigated, and a set of recommended alternative designs ordered on the basis of the net present worth of total cost is presented. The decision maker then selects a design.

Chapter 2 presents an analysis of existing concepts in rigid pavement design, their limitations, and assumptions involved in using those ideas. The descriptions of these concepts will be of value in further improvements of the present design procedure.

Chapter 3 is a brief description of systems concepts, their usefulness, and applications. A comprehensive systems formulation of the rigid pavement design problem and ideas applied to develop the present design procedure are discussed.

Chapter 4 summarizes the mathematical models used, their developments, and limitations.

Chapter 5 discusses the computer program developed, its input and output, and the optimization procedures adopted.

Chapter 6 presents a brief sensitivity analysis to establish initial confidence in the reasonableness of the solutions.

Chapter 7 summarizes the report and presents recommendations for future research and modifications.

CHAPTER 2. EXISTING CONCEPTS OF DESIGN AND ANALYSIS

Rational analysis and design of rigid pavements have long been a challenging problem for highway designers. The complexity of the vast multitude of variables to be considered has led to various approaches to analysis. The basic approach has been to use the theory of elasticity in solving various boundary value problems and then, after making certain assumptions to present the results of the analysis in an orderly form. Empiricism has been used to analyze and design the slabs for special cases.

From time to time during the 20th century the validity of these concepts has been assessed either by conducting laboratory experiments or by observing in-service pavements and controlled field experiments. Numerous reports of these investigations are scattered throughout the technical literature. This chapter presents a review of several existing concepts.

STRESS ANALYSIS AS A DESIGN CONCEPT

The structural analysis of rigid pavements has mostly centered around the evaluation of stress. The overstress giving rise to cracking in the structure has been considered as a principal indicator of failure of pavements. In turn, design of concrete pavements has centered around avoiding the formation of such cracking by keeping the level of stress below the allowable concrete strength. The stress analysis has mostly been carried out for two main factors causing the stress: loads and environment. Analysis with respect to these factors is described below.

Load Stresses

The analysis for load stresses has been attempted in the following categories.

Theoretical and Empirical Stress Analysis for Plates. The complete state of stress and the associated mechanical responses caused by bending in elastic plates were first analyzed by Timoshenko (Ref 131), who distinguished between the bending stresses in thin and thick plates and those in thin plates with small or large deflections. Pavement slabs are generally considered to be thin plates with small deflections. According to Timoshenko, the deflections of such plates under lateral loads can be described by the linear partial differential equation given below:

$$S_b \left(\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) = q - k \times w \qquad (2.1)$$

where

w = deflection at any point of the slab;

S_b = bending stiffness of the plate;

q = the applied lateral load;

$k \times w$ = the reactive pressure below the slab due to a bed of springs of stiffness, k , or the bouyant pressure of a dense liquid with density, k ;

x and y = standard Cartesian coordinate directions.

The solution of this equation gives the deflection at any point in the slab. The following assumptions were made in developing the relationship.

(1) There is no deformation of the middle plane of the plate during bending.

(2) Planes that are initially normal to the middle plane of the plate remain normal during bending.

(3) Normal stresses in the direction transverse to the plate are disregarded.

The empirical relationships and experimental investigations have always emphasized the importance of stresses near the corners of rigid pavement slabs. During the service life of a pavement, the corners in a pavement increase in number due to cracks intersecting with other cracks and with joints. A stage may therefore be reached in which every square yard of pavement is subjected to the stresses equivalent to the application of a load on a corner. Also, a corner break in turn generates increased wheel loads due to impact. These increased wheel loads on other corners of adjacent slabs cause them to break also. The corner area of rigid pavements, which is relatively vulnerable to overstress, has therefore been the subject of several major investigations, as described below.

The first attempt towards a design was made in 1919 when Goldbeck (Refs 38 and 39) suggested formulas for approximating stresses in a concrete pavement under certain assumed conditions of wheel load and subgrade support. Among these approximate formulas is one which has since become generally known as the "corner formula." The formula is derived by using the theory of elasticity and the following physical assumptions for applying the simple bending equation:

(1) The load is applied on the point of the slab corner.

(2) The corner receives no support from the subgrade and acts as a cantilever.

(3) The stresses in the slab are uniform in any section at a right angle to the corner bisector.

In 1923, extensive observations of rigid pavement cracking were made by Clifford Older at the Bates Road Test (Ref 86) conducted by the Illinois State Highway Department. The concept of corner breakage leading to the ultimate failure of pavement slabs was demonstrated in this test. It was observed that the points which represented the loads causing corner breaks and the thickness of broken slabs clustered around the curve given by Goldbeck's corner formula. Though none of the assumptions of the corner formula was present at the road test, good agreement between the observations and the corner formula was observed.

In 1925, the structural analysis of plates using the mathematical theory of elasticity was extended by Westergaard (Refs 142, 143, and 144) for pavement slabs. It was assumed in the analysis that the ordinary theory of thin plates was applicable and that the slab was a homogeneous, isotropic, elastic solid of uniform thickness in equilibrium on a continuous foundation.

Equation 2.1 was solved for three conditions, resulting in the following formulas for tensile stresses due to corner, edge, and interior loads:

$$\sigma_c = \frac{3L}{D^2}\left[1 - \left(\frac{a_1}{\ell}\right)^{0.6}\right] \qquad (2.2)$$

$$\sigma_e = 0.529(1 + 0.54\mu) \frac{L}{D^2} \left[\log_{10} \left\{ \frac{Eh^3}{kb^4} \right\} - 0.71 \right] \tag{2.3}$$

$$\sigma_i = 0.275(1 + \mu) \frac{L}{D^2} \log_{10} \left(\frac{Eh^3}{kb^4} \right) \tag{2.4}$$

in which

σ_c = maximum tensile stress in pounds per square inch at the top of the slab, in a direction parallel to the bisector of the corner angle and at a distance of $2\sqrt{a_1 \ell}$ from the corner;

σ_e = maximum tensile stress in pounds per square inch directly under the load and in a direction parallel to the edge;

σ_i = maximum tensile stress in pounds per square inch at the bottom of the slab directly under the load, which is at a considerable distance from the edge;

μ = Poisson's ratio for concrete;

E = modulus of elasticity of the concrete in pounds per square inch;

k = subgrade modulus in pounds per square inch;

a_1 = $\sqrt{2}a$ where a is radius of area of load contact in inches;

b = $\sqrt{1.6\, a^2 + D^2} - 0.675D$ when $a < 1.724D$
= a when $a > 1.724D$;

ℓ = radius of relative stiffness, defined by

$$\sqrt[4]{\frac{ED^3}{12(1 - \mu^2)k}}$$

L = load in pounds;

D = depth of slab in inches.

The radius of relative stiffness is a function of the "relative stiffness" of the slab and the support.

Distribution of load over a circular area of radius a in place of a point load as used by Goldbeck creates a reduction of the numerical values of the bending moments. Thus, Eq 2.2 predicts lower stresses than the corner formula proposed by Goldbeck unless the value of a is zero, in which case it is the same.

In 1942, Spangler (Ref 114) proposed Eq 2.5 for corner stresses on the basis of field observations and laboratory investigations at Iowa Engineering Experiment Station. The analysis led to the hypothesis that the locus of maximum moment produced in a concrete pavement slab by a corner load follows a curved path which bends towards the corner as it approaches the edges. Stress is not uniformly distributed along this path but is less at the edges than in the vicinity of the bisector. It is not necessarily so but is highly probable that any corner break would occur near the locus of maximum stress. It should be noted that the corner formula and Westergaard's formula were both based on the assumption of stresses uniformly distributed along lines normal to the corner bisector. Spangler's resulting stress formula is

$$\sigma_c = \frac{3.2L}{D^2}\left(1 - \frac{a_1}{\ell}\right) \qquad (2.5)$$

The formula as reported above is actually a simplification of Kelley's formula (Ref 65) which yielded the stresses which were compatible with the results of Spangler's experimental studies.

Picket (Ref 93) in 1951 proposed the following formulas as a result of his mathematical work.

For protected corners

$$\sigma_c = \frac{3.36L}{D^2}\left[1 - \frac{\sqrt{a/\ell}}{0.925 + 0.22\ a/\ell}\right] \qquad (2.6)$$

For unprotected corners

$$\sigma_c = \frac{4.2L}{D^2}\left[1 - \frac{\sqrt{a/\ell}}{0.925 + 0.22\ a/\ell}\right] \qquad (2.7)$$

These were proposed with considerations of lack of subgrade support under a corner as well as non-uniform distribution of moments along the sections perpendicular to a corner bisector. A later study (Ref 21) has graphically shown this formula to give favorable resulsts when compared with the other empirical formulas.

Numerical Solutions for Stresses in Plates. When the biharmonic equation 2.1 is derived in terms of bending and twisting moments, closed-form solutions give the exact state of stress, but such solutions are not possible by traditional calculus except for some specific cases of homogeneous, isotropic plates with simple loadings and boundary conditions. Pavements are not elastic and often contain discontinuities such as joints, cracks, and partial subgrade supports. There are varying conditions of loads, supports, and stiffnesses. Approximate solutions to these involved problems are made possible by the "numerical" methods developed in recent years.

Hudson and Matlock (Ref 59) have solved the differential equation by the substitution of finite-difference forms for derivatives. A thin plate has been modeled by a system of discrete elements as described in Fig 1 and the components of this model are grouped for analysis into an orthogonal system of beam-column elements and forces. A complete state of principal stress and deflection is obtained by solving a large number of simultaneous algebraic equations.

Further modifications to the concept were made by Stelzer and Hudson (Ref 120) and Pearre and Hudson (Ref 91). Kelly (Ref 64) modified the method to include nonlinear support characteristics.

A second numerical method known as the finite-element method has also shown promise (Refs 46, 108, and 153) but has not yet been applied successfully to the rigid pavement problem.

Layered System Analysis. With the successful application of numerical techniques and the computer, layered theory may prove useful for the analysis of complete state of stress and deflection in rigid pavements. In using such

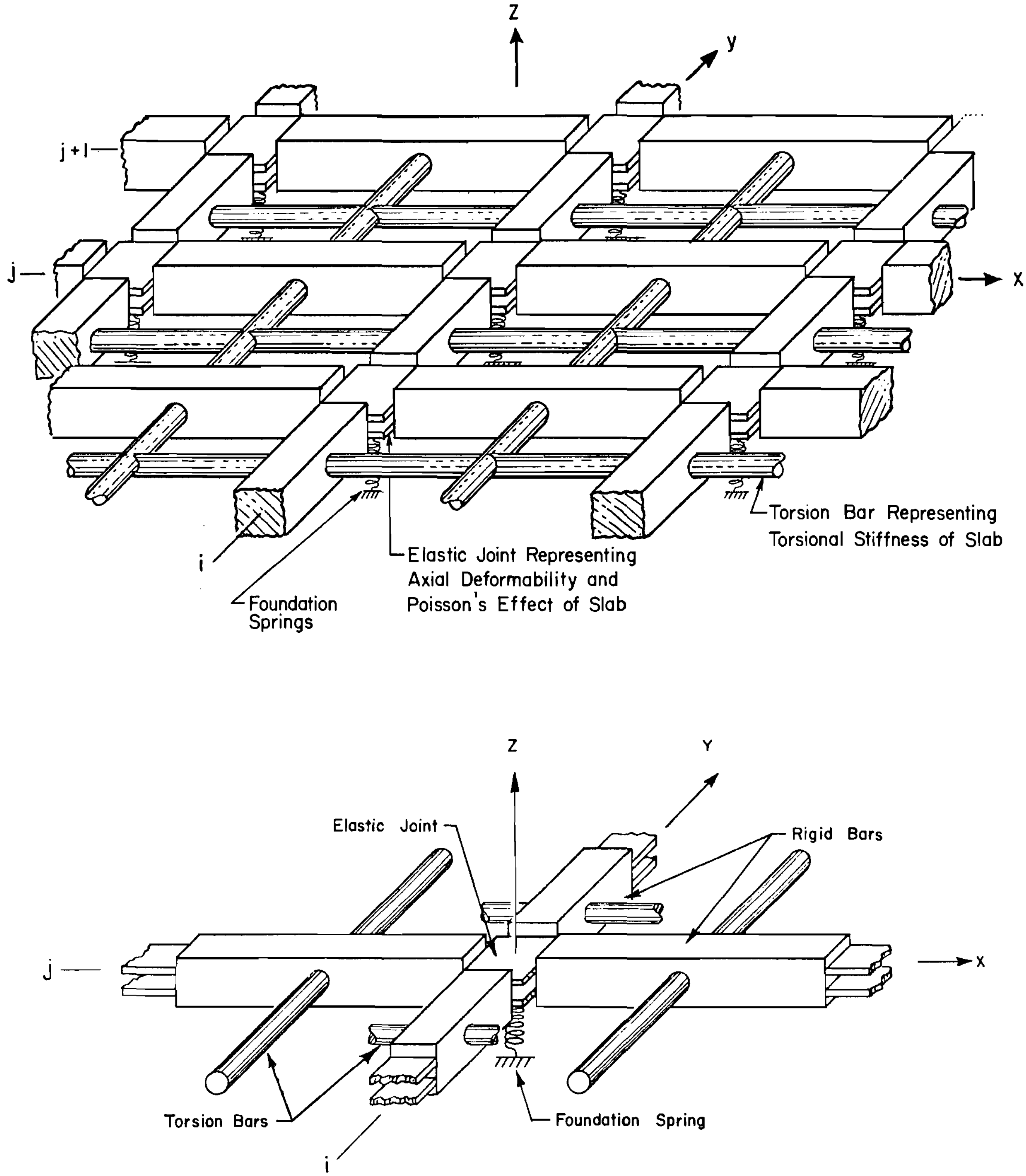


Fig 1. Finite-element model of a plate or slab and a typical joint i,j of the model (after Hudson and Matlock, Ref 59).

theory, layers of linear elastic materials of finite thicknesses and infinite horizontal extensions are assumed to be supported by a semi-infinite elastic subgrade. Stresses are obtained for axisymmetric cases and circular loads. This theory offers the relative advantages over the plate theory discussed earlier, in that

(1) complete state-of-stress beneath the top layer can also be obtained and

(2) vertical stress is considered as an integral part of the system.

The disadvantages of layered theory relative to plate theory, however, are that

(1) it cannot be applied at joints and cracks,

(2) it assumes layers of infinite horizontal extensions and therefore the exact state of stress at the edges and corners of pavement slabs cannot be evaluated,

(3) variable slabs cannot be handled, and

(4) loss of support cannot be input.

In 1885 Boussinesq (Ref 7), working on stresses in ideal masses, developed the first concepts of layered analysis and presented equations for vertical and radial stresses and elastic strains in perfectly elastic and homogeneous mediums. Foster and Ahlvin (Ref 36) developed charts for computing horizontal and vertical stresses and vertical elastic strains at any point below the surface due to circular loaded areas.

Burmister (Refs 9, 10, and 11) presented the first solutions for deflections directly beneath the load for one elastic layer on a semi-infinite elastic subgrade. This finite thickness layer was assumed to be elastic, weightless, horizontally infinite, and resting on a half space as used by Boussinesq. In addition, this top layer was assumed to be free of normal and shearing stresses outside the immediate load area. This analysis showed pronounced effects of relative stiffnesses of layers on stresses and deflections in the system.

Burmister's work was extended (Refs 45 and 92) to analyze for complete stresses and strains for three-layered systems. In addition, the states of full continuity and of zero continuity were also analyzed (Ref 45). A computer program is available that permits analysis of up to 15 layers. The program, developed by Shell Oil Company and Chevron Research Corporation, permits the use of any arbitrary number of layers, zero or full continuity between layers and the application of multi-loads. The finite-element technique is also employed by Duncan et al (Ref 29) to solve problems in pavement layered systems. Anisotropic conditions and nonlinear elastic problems can be solved with the technique presented.

A comprehensive study in relation to the applicability of layered theory for the analysis of rigid pavements is presented by McCullough (Ref 78). The results of layered theory are compared with those given by Westergaard's equations for stresses and deflections at the interior of a pavement slab and with comparable field data. Wide ranges of variables are tested in these comparisons. The following inferences are derived:

(1) Tensile stresses at the bottom of a concrete slab given by layered theory are in general agreement with tensile stresses predicted by Westergaard's interior formula over a wide range of parameters expected in practice.

(2) Deflections predicted by the two models differ highly, especially for low values of subgrade modulus. In general, layered theory predicts two to four times more deflection than the Westergaard interior equation.

(3) Strains predicted from the layered theory agree reasonably well with those measured on experimental projects, but predicted deflections are considerably higher than those measured in the field.

(4) Assumed subgrade thicknesses of 2 to 12 feet (in place of infinite) resting on a stiff layer cause significant improvement in the deflections predicted by layered theory. Subgrade thicknesses also have a considerable effect on tensile stresses, but the stresses are not as sensitive to these thicknesses as are the deflections.

A typical comparison of tensile stresses predicted by two theories is shown in Fig 2.

Environmental Stresses

Various environmental factors affect the mechanical state of the pavement and thus produce stresses. The most important environmental factor which has been a matter of wide interest in the past is temperature. Temperature in a concrete pavement constantly changes due to variations in air temperature which take place at a relatively rapid rate. These changes in slab temperature can be divided into two parts:

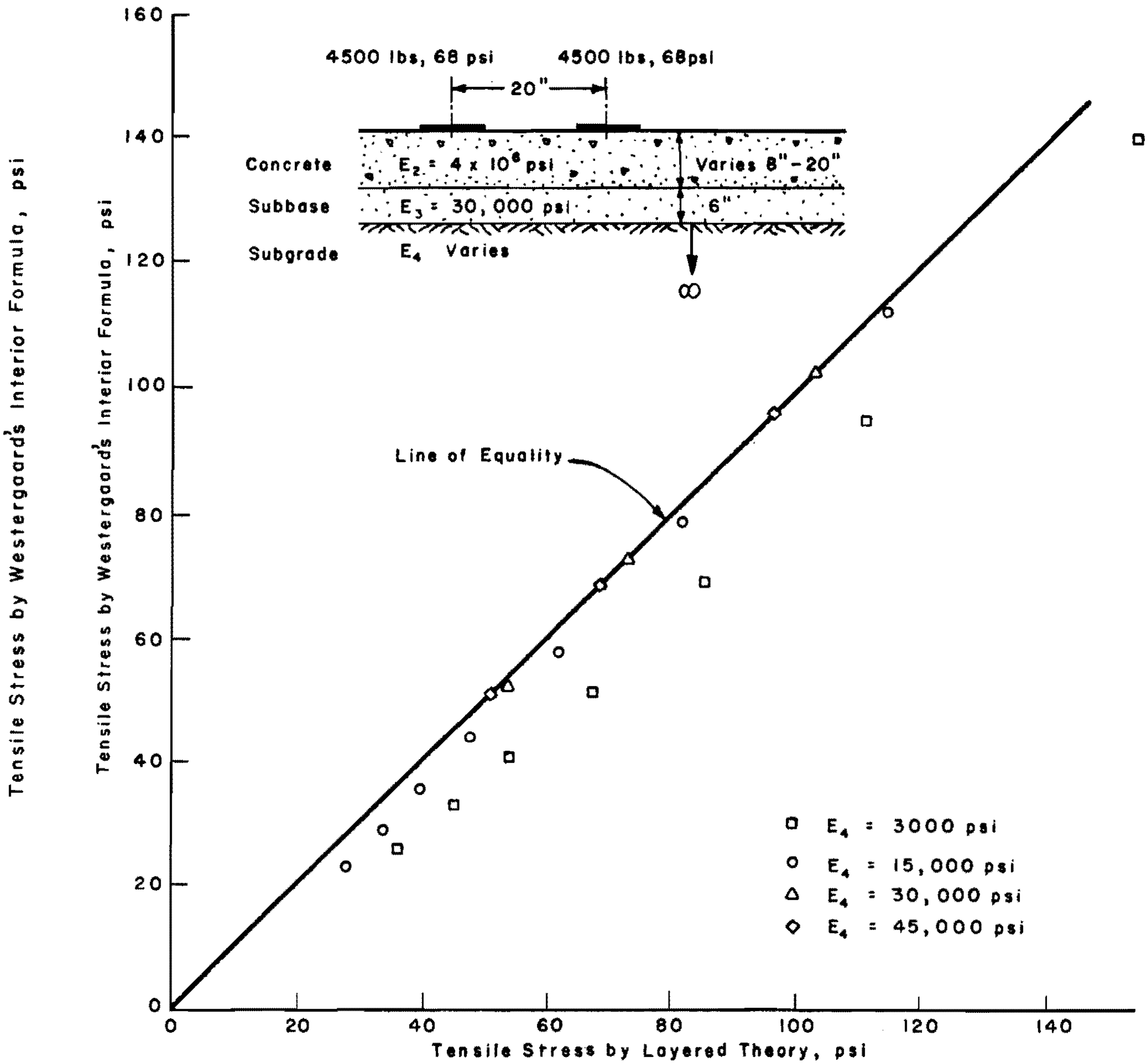


Fig 2. Comparison of internal load pavement subbase interface stresses computed by Westergaard and layered theory for varying subgrade modulus and pavement thicknesses, dual wheels (after McCullough, Ref 78).

(1) the daily and seasonal variations in the average temperature of the slab and

(2) daily variations between the top surface and the bottom.

One leads to volume change stresses whereas the second produces curling and warping stresses in concrete pavements.

Temperature Volume Change Stresses. Variations in the average temperature give rise to frictional forces between the slab and its support. Generally the slab tries to adjust itself to the slowly changing seasonal temperature conditions, thereby avoiding excessive stress conditions; but an appreciable fall in mean temperature of the slab in a relatively short time, at night or in cold weather, gives rise to considerable tensile stresses at or near the midpoint of the slab. Thus, the maximum contraction stress in a pavement slab is not necessarily dependent on the annual change in temperature. It is more dependent upon subgrade resistance that can be developed during a single period of continuously falling temperature, or at most during relatively few cycles of temperature changes in which the general level of the minimum temperature is decreasing. It has been observed that the daily change in average slab temperature is generally less than the daily change in the air temperature and the relation between the two is influenced by the season of the year and by the particular climatic conditions. Also, it has been observed experimentally (Ref 65) that in general the maximum daily change in the average slab temperature is less during the cold months of the year than during the warm months.

Westergaard (Ref 145) has presented a theoretical analysis of contraction stresses in the central area and the edge of a very large panel of a slab by assuming that the friction is sufficient to prevent the slab from contracting in either direction. Based on experimental observations, Kelley (Ref 65) also presented the analysis of such stresses generally known as the "subgrade drag theory." This analysis, in place of coefficient of expansion of concrete, makes use of a variable coefficient of friction developed at the bottom of the slab due to its contraction. The approach has been used for the design of reinforcement in RPS1 and is described in Chapter 4.

Temperature Curling Stresses. The daily changes in the differential in temperature between the two surfaces of the slab cause it to curl. Since this curling is prevented by the weight of the slab, considerable bending stresses are induced. The magnitudes of these stresses under certain conditions are quite comparable to the load stresses. The significance of temperature differential in the slab is not only due to the stresses induced by curling but also to the decrease in subgrade support caused by the slab moving away from the subgrade.

In 1926, Westergaard (Ref 145) presented a theoretical analysis of curling stresses for slabs of infinite lengths and widths and for those of finite widths and infinite lengths. On the basis of the concepts of Westergaard's analysis, Bradbury in 1938 (Ref 8) presented the general equations for temperature curling stresses in the corners and interiors of pavement slabs of usual dimensions. The second elastic theory for the estimation of curling stresses was presented in 1940 by Thomlinson (Ref 130). The theory assumes a nonlinear temperature gradient in the slab as compared to linear distribution assumed by Westergaard. Thomlinson assumed that the heat supplied to the concrete slab is such as to produce a simple harmonic variation of temperature at the exposed surface. Observations by Bergstrom, Sparkes, Venkata Subramanian (Refs 4, 116, and 135), and others have shown that the assumption of nonlinear temperature gradient is experimentally true to a certain extent, expecially during hot clear days.

An exact analysis of stresses in concrete pavements must add the curling and the frictional stresses to the load stresses. The combined stress in the edge loading case for daytime when the edges are curled downwards is reported to be the maximum (Ref 65) for a certain range of slab lengths, soil moduli, and slab thicknesses.

Stresses Due to Moisture Variations. The moisture variations in concrete slabs create stresses in much the same manner as do the temperature variations. A moisture loss from the top surface of the slab will make the slab warp upwards and vice versa. A stress analysis for moisture can be obtained on the same basic lines as those of stress analysis due to temperature variations (Ref 145).

Theories of Support Media Used in Stress Analysis

Support below a concrete slab has usually been represented by two theories, a dense liquid or Winkler's model and a semi-infinite, elastic, isotropic, solid.

The dense liquid approach was first introduced by Winkler (Ref 149) in 1867. According to this approach, the foundation is represented by a bed of linear springs having a spring stiffness equal to k or as a dense liquid having a density equal to k . Vertical reactive pressure at any point is therefore equal to k multiplied by the deflection. The constant has been widely used in the theoretical analysis dealing with plates by, among others, Hertz (Ref 47) and Westergaard (Ref 143) and in the numerical analysis of plates by Hudson and Matlock (Ref 59). The modulus has always been assumed to be independent of the deflections and constant at all points within the area of consideration.

In the second theory, the subgrade is considered as an elastic, isotropic, Hookean, semi-infinite solid defined by its modulus of deformation and Poisson's ratio. The approach has been used in the analysis of layered systems as described earlier. The approach has also been widely used for the analysis of thin elastic plates. Hogg (Ref 49) and Holl (Ref 51) independently analyzed for deflections of a thin elastic plate of infinite size resting on the so-called "infinite half space." Among those using this approach are Bergstrom, Biot, Picket and Ray, and Vesic (Refs 5, 6, 94, and 136).

According to Vesic and Saxena (Ref 137) major attention in the structural analysis of rigid pavements should be devoted to the evaluation of models representing supports. Predictions based on Winkler's assumption show good agreement with the observed responses of rigid pavements, but an elastic isotropic solid model may, as shown by the existing evidence, simulate the soil response to loads more closely than does Winkler's model. Terzaghi (Ref 125) in a critical analysis of k value accepted its usefulness in giving reasonable estimates of stresses in slabs, provided its correct value can be selected. On the other hand, he also accepted that this constant had little to do with the actual responses of soils to loads.

Extending Biot's analysis, Vesic (Refs 136 and 138) presented an expression for selecting a value of k which can obtain good approximations of both bending moments and deflections of an infinite beam resting on an elastic, isotropic solid. For plates, "there is no single value of k that can yield agreement of all statical influences, such as pressures, shearing forces, bending moments, and deflections, across the slab" (Ref 137). However, a value k_o , modulus of support reaction, can be computed in terms of the parameters of elastic subgrade solid which would give the same bending moments in the vicinity of the load in either analysis. The relation given is

$$k_o = 0.91 \sqrt[3]{\frac{E_s (1 - \mu^2)}{E (1 - \mu_s^2)}} \frac{E_s}{(1 - \mu_s^2)D} \qquad (2.8)$$

where

E_s = modulus of deformation of subgrade material,

E = modulus of elasticity of slab material,

μ_s = Poisson's ratio of subgrade material,

D = slab thickness.

According to the above equation, k is not a characteristic of the subgrade material only but is also a property of the combined slab and subgrade system. It is indicated that good agreement in the slab deflections can also be achieved by using the above value of k_o, provided the subgrade is assumed to be of finite depth. In that case, the expression suggested for subgrade modulus is

$$k_o' = \frac{1.38\ E_s}{(1 - \mu_s^2)H} \quad \text{when} \quad \frac{H}{D} < 1.38 \sqrt[3]{\frac{E}{E_s}} \qquad (2.9)$$

where

H = the thickness of elastic isotropic subgrade.

The modulus of subgrade reaction k can be determined in the field by plate loading tests (a comprehensive analysis is given in Ref 82) or by loading the existing slabs (Refs 124 and 143). Skempton (Ref 111) has presented a procedure for determining the load-deflection curve of a plate on a saturated clay from the data obtained in the laboratory on compression tests of such soils. Lee (Ref 69) and Seed et al (Ref 106) have demonstrated the usefulness of the approach to predict the deflection of circular plates under static and repetitive loads.

PERFORMANCE AS A DESIGN CONCEPT

The design methods developed on the concepts discussed above are based on concrete stress, a primary response of the pavement system. The thickness of the slab is determined by one criterion, holding the stress in the slab below a certain level. The cracking mechanism of distress which results from loads that produce overstress has been considered a catastrophic event leading to the failure of the structure.

It is accepted that overstress produces a crack, which is undesirable, but it is not the only state that has to be determined in designing a pavement system. Pavement in its cracked state continues to perform its function, although possibly at a reduced service level. Failure is an unacceptable performance condition which develops gradually over a span of life due to the accumulated effects of the distress manifestations rupture, distortion, and disintegration. These manifestations are the functions of loads, environment, construction, maintenance, location, and time (Ref 56).

The three manifestations of failure given above can be weighted and combined through a mechanistic model into a single response called the serviceability level of the pavement. The best effort in this direction was made at the AASHO Road Test, where certain pavement characteristics measured objectively were related to the user's subjective evaluations of the ability of the highway to serve them. This present serviceability concept is perhpas the most significant single item developed from the Road Test. Present serviceability index is used to represent the riding quality of a pavement and is defined as the ability of the pavement to serve high-speed, high-volume mixed truck and automobile traffic in its existing condition.

The mechanistic model with statistically assigned weighting functions to certain objectively measured distress factors on portland cement concrete pavements is given as

$$PSI = 5.41 - 1.78 \log (1 + \overline{SV}) - 0.09 \sqrt{C_a + P_a} \qquad (2.10)$$

where

PSI = present serviceability index;

$\overline{SV}$ = summary statistic of wheel path roughness as measured by the Road Test longitudinal profilometer and mathematically defined as the average squared deviation of slope from its mean,

C_a = class 2 and sealed cracks, in feet per 1000 square feet,

P_a = patched area in square foot per 1000 square feet.

The present serviceability concept at the AASHO Road Test was developed and reported initially by Carey and Irick (Ref 13). A short discussion of pavement roughness and its measuring devices is presented in Refs 12 and 54. A high-speed profilometer is evaluated, and regression equations to predict pavement serviceability which were developed for the Texas Highway Department are discussed by Roberts and Hudson in Ref 98.

AASHO Road Test Equation

The serviceability trends of the pavement sections at the AASHO Road Test led to a basic assumption that serviceability loss in any trend was proportional to a power function of the axle load applications.

Defined mathematically,

$$P_1 - p = CW^{\beta} \tag{2.11}$$

where

P_1 = the average of all initial trend values for Road Test sections,

p = the serviceability trend value of the section at any time,

β = a positive power depending on the load and design variables,

W = the number of axle load applications,

C = a constant.

Rearrangement of Eq 2.11 gave

$$\text{Log } W = \log \rho + \frac{G}{\beta} \tag{2.12}$$

where

$$G = \log \frac{P_1 - p}{P_1 - p_L} \tag{2.13}$$

p_L = serviceability index at which a section was 'out of test' at the Road Test - a value of 1.5 was selected,

ρ = value of W when $p = p_L$, i.e., ρ was the experimental life of a section.

It may be noted that β determines the shape of the serviceability trend for a section. A value of β equal to 1.0 shows the serviceability loss to be linear as the applications increase, whereas β greater than 1.0 shows the serviceability loss to be declining along a steeper and steeper curve with the serviceability loss rate increasing with applications.

The values for β and ρ were determined as

$$\beta = 1.0 + \frac{3.63(L_1 + L_2)^{5.20}}{(D + 1)^{8.46} L_2^{3.52}} \tag{2.14}$$

$$\rho = \frac{10^{5.85}(D + 1)^{7.35} L_2^{3.28}}{(L_1 + L_2)^{4.62}} \tag{2.15}$$

where

L_1 = axle weight, in kips;

L_2 = one for single axles, two for tandem axles;

D = slab thickness.

For an 18-kip single axle load which is adopted as a single parameter for use in the present design system, Eq 2.12 reduces to

$$\text{Log } W_{18} = \log \rho_{18} + \frac{G}{\beta_{18}} \tag{2.16}$$

where

$$\beta_{18} = 1 + \frac{16.196 \times 10^6}{(DT)^{8.46}} \tag{2.17}$$

and

$$\rho_{18} = .87533 \ (DT)^{7.35} \tag{2.18}$$

(D + 1) is denoted as the thickness design term DT . W_{18} is the number of 18-kip single axle load applications.

Modifications of AASHO Road Test Equation

In their general form the relationships shown above have limited applicability because they only relate the slab thickness, magnitude, and configuration of axle load and load applications to the performance of a section.

To develop a procedure to apply the equations to the structural design of rigid pavements in physical environments which generate external and internal influences appreciably differing from those which existed during the Road Test, it is necessary to adopt certain modifications to these equations to achieve a rational design procedure.

Two modified forms of the AASHO model have been presented thus far (Refs 57 and 61). The first was carried out by an AASHO Subcommittee on Design (Ref 68), which was assigned the responsibility of developing new pavement design procedures utilizing the results of the AASHO Road Test. The subcommittee developed the following straight line correlation:

$$\text{Log } W_{18} = a + b_t \log S_x/\sigma_{cs} \tag{2.19}$$

where

S_x/σ_{cs} = the ratio of flexural strength of concrete to the corner stress calculated by the Spangler equation for the Road Test pavements,

a = a constant,

b_t = the slope of the straight line defined by Eq 2.19 and is a function of terminal serviceability p, as

$$b_t = 4.22 - 0.32\, p \tag{2.20}$$

Substituting Eq 2.19 into the basic AASHO equation, the following correlation was obtained:

$$\text{Log } W_{18m} = \text{Log } W_{18} + \text{Log } C_F \tag{2.21}$$

where

W_{18m} = the modified number of 18-kip single axle applications that a pavement with different physical properties will sustain

and

$$\text{Log } C_F = b_t \text{ Log} \left[\frac{f_c\left(1 - \frac{1.1326}{D^{.75}}\right)}{215.625J\left(1 - \frac{a_1}{\ell}\right)} \right] \tag{2.22}$$

where

f_c, J, a_1, and ℓ are the parameters of the pavement being designed,

f_c = allowable flexural strength of concrete,

J = load transfer characteristic coefficient = 3.2 for free corners,

$a_1 = \sqrt{2}\,a$, where a is radius of a circle equal in area to the loaded area. Assumed value of $a_1 = 10$

and

$$\ell = \sqrt[4]{\frac{ED^3}{12(1-\mu)k}} \tag{2.23}$$

where

E = modulus of elasticity of concrete;

μ = Poisson's ratio of concrete, assumed to be equal to 0.20;

k = modulus of subgrade reaction.

The second attempt to modify the basic AASHO equation (Ref 57) involves the use of corner load stresses observed at the Road Test and their correlation with the thickness design term DT .

Corner stresses σ_{18} given by 18-kip single axles in Loop 1 of the AASHO Road Test are related to the stresses predicted by Spangler's equation, σ_{cs} , by the correlation

$$\sigma_{18} = 0.301\sigma_{cs}^{1.01} \tag{2.24}$$

Also, the thickness design term was correlated to σ_{18} by

$$DT = \frac{98.855}{\sigma_{18}^{.517}} \tag{2.25}$$

Substituting Eq 2.24 in 2.25,

$$DT = \frac{183.9}{\sigma_{cs}^{.5222}} \tag{2.26}$$

For the purpose of inserting the flexural strength of concrete into the design equation, it was assumed that the term σ_{cs} can be replaced by $\sigma_{cs} \frac{S_x}{f_c}$ where S_x is the fixed flexural strength of Road Test pavements (690 psi ± random variation) and f_c is the flexural strength of any concrete used in design.

Thus W_{18m} in this case is given as

$$\text{Log } W_{18m} = 7.35 \text{ Log } (DT_m) - 0.05782 + \frac{G}{1 + \frac{16.196 \times 10^6}{(DT_m)^{8.46}}} \qquad (2.27)$$

where

$$DT_m = \frac{183.9}{\left(\sigma_{cm} \frac{690}{f_c}\right)^{.5222}} \qquad (2.28)$$

and

$$\sigma_{cm} = \frac{JL}{D^2}\left(1 - \frac{a_1}{\ell}\right) \qquad (2.29)$$

L , J , a_1 , ℓ , and f_c are defined in Eqs 2.5, 2.22, and 2.23.

EXISTING CONCEPTS APPLIED TO PAVEMENT DESIGN PROCEDURES

The design of rigid pavements has mostly been based in the past on the criterion of limiting stresses and therefore the empirical and semi-empirical formulas described above have been widely used for the design of rigid pavements by predicting such stresses. Corner loads have been of primary interest because of the higher magnitude of stresses they produce as compared to other load positions. The use of standard sections of concrete pavements has also been adopted by various design agencies. The standard sections were evolved through the design of concrete thickness by empirical stress formulas and the subsequent observations of the performance of such designs under actual field conditions.

The design of rigid pavements has been evolved by different agencies in the form of simple tables of standard thicknesses, charts, curves, nomographs, and in one case a somewhat more refined procedure by the Portland Cement Association (Ref 128). The main basis of all procedures has been the attempt to hold the level of stress computed by an empirical formula below a certain level.

Various design criteria have been developed in the past to be used with empirical stress formulas. The allowable stress in concrete has always been specified with a large factor of safety, to take into account the stresses developed due to unforeseen factors not accounted for in the design. Allowable concrete stress has generally been specified as one-half of the concrete flexural strength, to account for the fatigue of concrete due to repeated stress applications. The factor of safety is based on the fatigue curves of concrete which show that a pavement can sustain unlimited load applications without a failure if the maximum stress produced does not exceed one-half the flexural strength.

The load for which the pavement is designed has been represented by various criteria such as

(1) maximum anticipated load during the life of the pavement,
(2) predicted average value of a particular number of highest loads,
(3) n^{th} highest load where n is a specified number, or
(4) a specified legal load.

The load thus determined has mostly been increased by a ratio or safety factor depending upon general engineering judgment to take into account the dynamic nature of highway loads.

The Portland Cement Association in 1951 (Ref 21) presented a procedure for designing concrete sections for highway pavements. The procedure is based on the empirical corner stress formula proposed by Picket (Ref 93).

The pavement is designed for a controlling wheel load which is the average of the heaviest 100,000 anticipated wheel loads. The loads are increased by 20 percent for impact, and a factor of safety of 2 is used for allowable flexural strength of concrete. The effect of loads heavier than the controlling wheel loads is checked by the fatigue resistance consumed by heavier load groups. It is stated that pavements designed by this method have enough excess strength to offset the curling stresses also.

The Portland Cement Association in 1966 modified the design procedure (Ref 128). The following are the main features of the modification:

(1) The stress is computed by charts developed for single and tandem axle loads at transverse joint edges. The charts are prepared by using influence charts developed by Picket and Ray (Ref 94).

(2) Different load safety factors are proposed for various types of facilities to be designed.

(3) Traffic is projected with the help of standard charts using design life and a yearly rate of traffic growth.

(4) The design is based on a method which computes fatigue resistance used by each load group.

(5) Increase in modulus of subgrade reaction due to subbases is considered by the use of tables which are based on Burmister's analysis of the two-layer systems.

A second design procedure is based on the performance concept and is developed using AASHO Road Test data. The procedure is reported in the Interim Design Guide (Ref 61). The design equations are developed by modifying the basic AASHO Road Test equations. Design can be carried out by the use of charts presented in the guide (the method is for the design of jointed concrete pavements only). Rigid pavement thickness for a design life of 20 years is designed by this procedure, using the following values:

(1) equivalent daily 18-kip load applications,

(2) working stress in concrete,

(3) modulus of support reaction, and

(4) final Serviceability Index value.

By using the modified equation (given in the Interim Design Guide) in place of charts, two more variables can be considered in design:

(1) modulus of elasticity of concrete, and

(2) initial Serviceability Index value.

Two design procedures based on two different concepts of analysis are described above. These are by far the best methods available for design of rigid highway pavements.

Various concepts related to the analysis of rigid pavements are discussed in this chapter. The concepts show great promise in understanding and quantifying different models of design and analysis. Layered theory and numerical plate solutions can achieve, for the first time, a complete analysis of stresses and deflections in rigid pavement structures. Theories for support media help understand the most controversial phase of rigid pavements, i.e., how to represent the strength of foundation materials. Theories for temperature stresses take into account probably the most important environmental factor affecting the mechanical state in rigid pavements. The performance concept is the latest and by far the best concept for understanding the progressive failure of rigid pavements. An understanding of these concepts of rigid pavement design and the study of referred literature will help develop a basic understanding and the directions for accomplishing a more rational procedure for the structural analysis and design of rigid pavements. Such a conceptual procedure of design is discussed in the next chapter.

CHAPTER 3. SYSTEMS ANALYSIS OF RIGID PAVEMENT DESIGN

Pavements are complex structures. This is mostly due to the variety of loads, materials, and environments but is also due in part to various economic parameters involved. To simplify the problem, existing design procedures have always been oriented towards emphasizing certain important features of design and neglecting others even though they may have significant effects. A good description of the problem, a new insight into the complexity, and an optimization of techniques in the face of various economic criteria may lead to achieving a rational pavement design procedure. This chapter is directed towards the application of systems engineering to this design problem.

A system can be described as a device, procedure, or scheme which behaves in a describable manner to accomplish an operational process (Ref 56). Accordingly, pavement is defined as a system which obeys physical laws to transform the effects of input variables into various responses leading to pavement distress or success. Design of such a system needs a coordinated set of procedures to detail the use of money and materials in the most economical combinations. Such a procedure of resource allocation is a system and should be carried out by the application of classical economic concepts.

Systems concepts help accomplish an operational process in the most efficient manner through an integrated approach rather than a piecemeal synthesis of important parts. The entire system is viewed as an entity and not as an assembly of individual parts functioning by themselves. The most successful system does not necessarily require the individual parts to be operating most efficiently at all times. An integrated approach can achieve this efficient system by trade-offs among the different interests of its various subsystems.

The coordinated approach towards the solution of the overall problem, called systems analysis, offers several advantages:

(1) The development of a complete problem description provides new insight and perspective into the complexity of the problem, including the feedbacks and interactions involved.

(2) This insight, in turn, provides a structure for coordinating and utilizing research from many sources.

(3) A system description rapidly points out the areas of weakness and, consequently, areas of urgently needed research.

(4) A coordinated approach to the problem helps in understanding and developing the functions and theories which can be used to determine optimal choices of designs in the face of various judgment criteria and weighting functions.

(5) The analysis permits the use of various techniques in optimization and operations research to solve the problem.

(6) In the process of developing an overall optimal solution, immediate benefits can be gained by use of current state-of-the-art information in the systems framework until better techniques of analysis are developed.

PHASE DEVELOPMENT OF CURRENT DESIGN PROCEDURES

In attempting to apply the concepts to the design of rigid pavements, existing design procedures will be used as a first step in a systems framework. These procedures in fact are the first phase of the ultimate system to be developed. Figure 3 is a simple systems diagram of the early rigid pavement design procedures. The diagram shows a constant feedback from the actual behavior of highway pavements to the formulation of design criteria for satisfactory designs.

Formulation of design criteria has been refined by successive cycles of designing new pavements and observation of their performance. Satisfactory designs have generally been repeated for construction and the designs which performed poorly have been discontinued. In both cases, the observations added to the design criteria existing at the time helped to modify them for future use.

Early design procedures, when viewed in a systems framework, exhibit a number of deficiences (Ref 60):

(1) The mechanisms of pavement failure in these procedures are poorly defined. The progressive and cumulative nature of pavement deterioration is not considered; rather, the pavement failure is assumed to be indicated by such primary responses of the system as deflections and stresses. A pavement is termed to be satisfactory or unsatisfactory and the concept of the degree of dissatisfaction is not defined. In other words, no correlation is established between the design and performance.

(2) Environmental effects are not quantified and are taken into account only in a subjective way. The design procedures are, therefore, not widely transferable from one geographic locality to another.

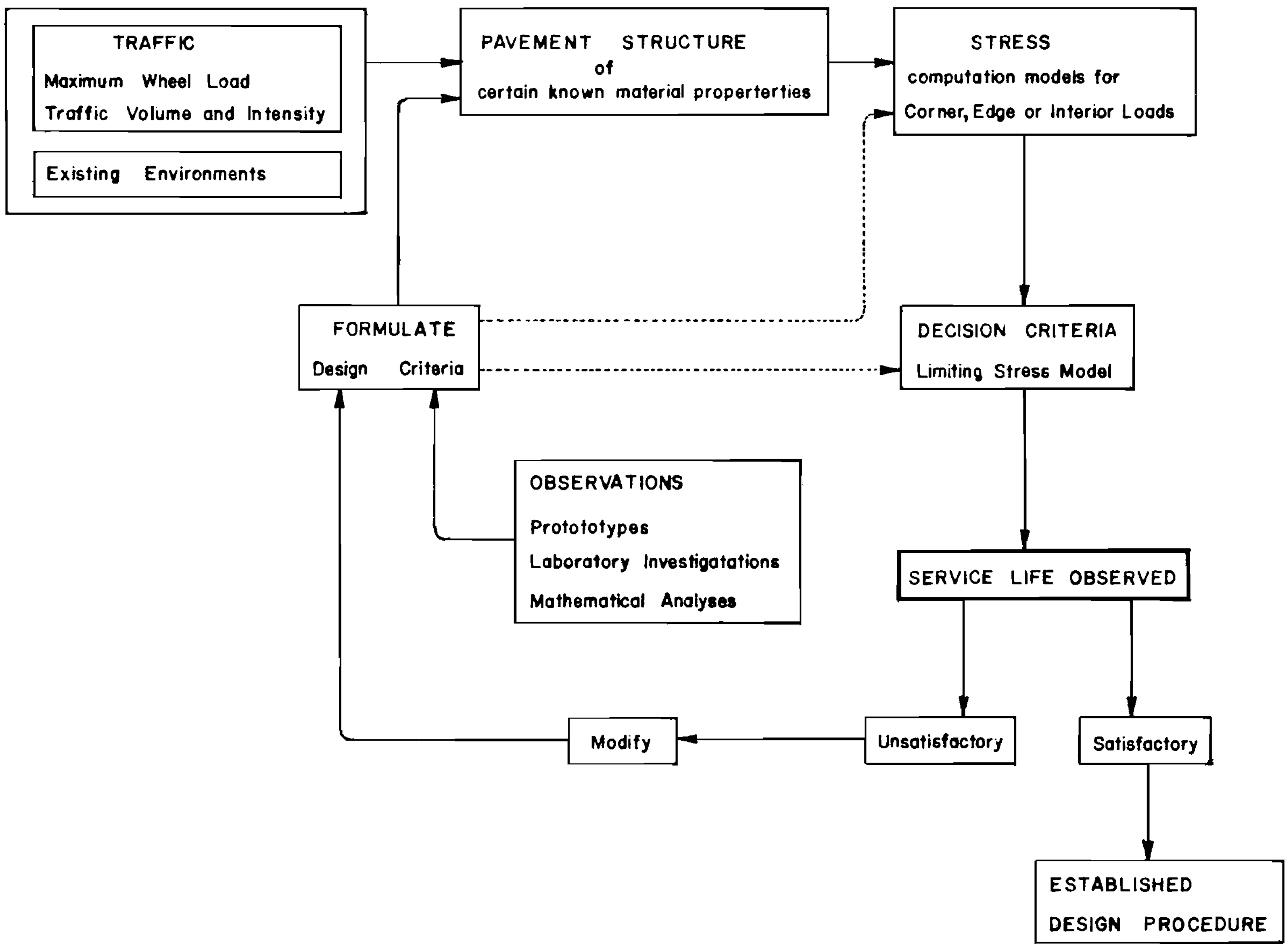


Fig 3. Development of early rigid pavement design methods.

(3) Variations in material and construction qualities cannot be taken into account.

(4) The optimization between the alternative pavement strategies is not possible because of the lack of data and procedures for economic comparison of alternatives.

FORMULATION OF AN IDEAL DESIGN SYSTEM

According to the system definition stated above, a comprehensive formulation of the design process characterizing various technical and economic aspects is needed before a more realistic pavement design system can be proposed for immediate use involving state-of-the-art information. Figure 4 details an attempt to describe many factors involved in a conceptual rigid pavement system.

Physically, the pavement system can be defined as an operator which when acted upon by the excitation functions gives system responses. The response is generally characterized by an immediately observed mechanical state defined by stresses, strains, deflections and coefficient of friction between the tire and the pavement surface, and eventually by the time-dependent accumulated effects of these primary responses in the forms of rupture, distortion, disintegration, and low friction.

System excitation variables, often termed as system inputs, have been the subject of a great amount of research with respect to their effect on the system and its responses. An example to this effect is given of various models developed in the past to predict the stresses and deflections due to loads applied on the system. System inputs and their main effects are described in the following sections.

SYSTEM DESCRIPTION AND INTERACTIONS

System Inputs

The effect of loads caused by traffic is to create a certain mechanical state in the pavement at a certain time. The materials in the system respond to this mechanical state in various ways. Main load variables are

(1) magnitudes;

(2) distribution with respect to time as frequency, rate, and duration;

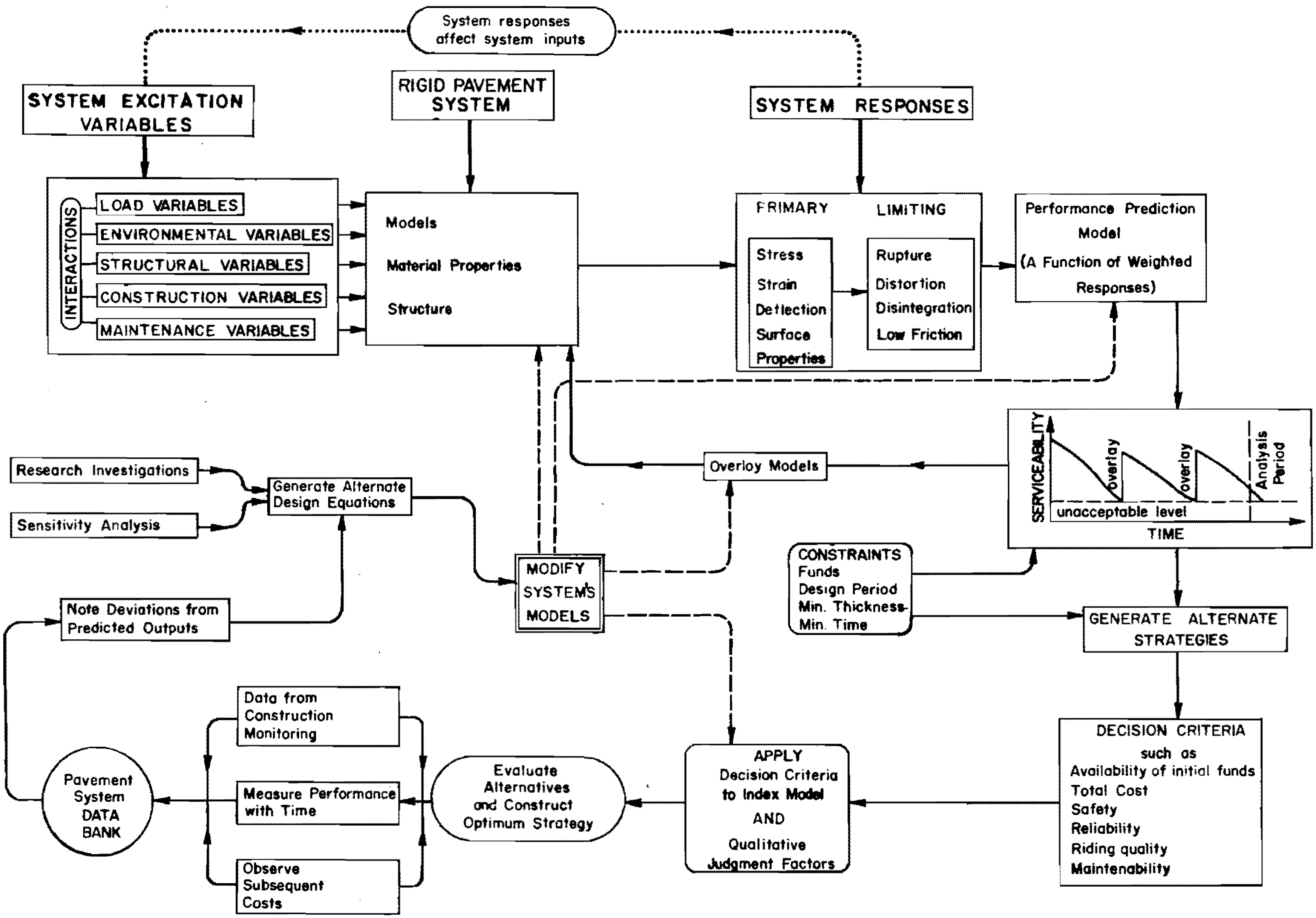


Fig 4. Conceptual rigid pavement design system.

(3) total accumulated applications; and
(4) distribution with respect to placement.

An excessive magnitude of load can produce a well-known distress mode called rupture through overstress, whereas the repeated application of stress to pavement materials with nonlinear viscoelastic properties can produce system distortion and rupture through such phenomena as fatigue (Refs 16, 66, 74, 84, and 85) and creep in concrete and other support materials. Magnitude of load and repeated applications also produce physical disturbances in subbases and subgrades with respect to the macroscopic reorientations of the material structures resulting in densification, distortion, and failures.

Environmental inputs are varied and cyclic. Among them are temperature, moisture, humidity, and rainfall. Temperature variations and their magnitudes, frequencies, and durations produce stresses in the pavement structure due to warping, expansion, and contraction. Moisture and humidity variations in concrete slabs affect stresses in much the same manner as temperature. Rainfall affects the ground water conditions which may produce such physical results as pumping and loss of support. Maintenance is also an external input to the system, but its intended effect, contrary to other inputs, is to increase the life of the system by improving the system's responses as well as riding quality.

There is frequently interaction among various inputs to the system. Environment, for example, may affect the volume of traffic or the amount of maintenance required; or the presence of moisture may affect the amount and distribution of heat in and beneath the pavement.

The System

The physical system is characterized by the material properties, material arrangements, amount of materials and the shape given to them, and the quality of construction. The material properties of the system as constructed, generally described by various engineering characteristics, are very important parameters of the system. The basic properties of materials are complex physical functions dependent upon numerous parameters. The significant basic properties, for engineering purposes, are defined as functions which quantify material responses to one or more external inputs and are necessary to compute responses of the pavement system. Materials are nonlinear viscoelastic in nature and their properties are never constant over time. Inputs such as loads and environments are the main reasons for the ever changing basic properties of the materials.

The following general phenomena are important in rigid pavements with respect to interactions within the system:

(1) excessive loads change load deformation characteristics of pavement materials,

(2) repeated stress applications produce fatigue and creep in paving materials,

(3) densification and consolidation of support materials affect their characteristics,

(4) thermal and moisture variations in concrete change its properties,

(5) moisture variations in subgrades stimulate their swelling characteristics, and

(6) traffic produces surface abrasion.

System Responses

System responses consist of two types, primary and limiting. Primary response is defined by the mechanical state (stresses, strains, deflections, and surface characteristics) of the system, whereas limiting response is obtained by the progressive effects produced due to the repetitive existence of the state of primary response. The limiting response is the actual criteria of failure of pavements.

Limiting response interacts with inputs such as loads and maintenance. Roughness of a pavement at any time influences the dynamic magnitude of the traffic loads and the maintenance required.

As defined by Hudson et al (Ref 56) the limiting response denoted as distress can be conceptually expressed as

$$\underline{DI}(\underline{x},t) = \underset{s=o}{\overset{s=t}{\underline{F}}} \left[\underline{C}(\underline{x},t),\ \underline{S}(\underline{x},t),\ \underline{D}(\underline{x},t)\underline{x},t \right] \tag{3.1}$$

where

t = time;

$\underline{x}$ = position vector of a point referred to in a coordinate system;

$\underline{DI}(\underline{x},t)$ = distress index, a matrix function of space and time;

$\underline{C}(\underline{x},t)$ = measure of fracture, a matrix function of space and time;

$\underline{S}(\underline{x},t)$ = measure of distortion, a matrix function of space and time; and

$\underline{D}(\underline{x},t)$ = measure of disintegration, a matrix function of space and time.

The progressive deterioration of pavement is of great importance in its systematic design which takes into account its interactions with inputs and effects on human responses. Discomfort to the rider is a measure of pavement deterioration. The vibrations of a vehicle moving on a pavement determine this discomfort and are functions of factors such as suspension characteristics of vehicles, their speeds, and pavement roughness (Refs 40 and 60).

The average of these human responses characterizes the serviceability of a pavement, i.e., the extent to which the traveling public is served. Serviceability-age histories of pavements are essential to evaluate the cost implications of the system.

Development of mathematical theory to compute the distress index DI in the above equation will require a comprehensive set of models for input assessment, material behavior, primary and limiting outputs, and finally the human responses to the motions generated. As an alternate, the best procedure presently available involves the Present Serviceability Index equations developed at the AASHO Road Test. These equations were developed by correlating the subjective ratings of pavements to their objective characteristics, thus bypassing the formulation of models for the individual subsystems described above.

Solution Generation and Evaluation

This phase of the system process involves generation of potential alternative strategies and their evaluation for the selection of the best. A strategy is defined as a set of resource allocations necessary for a design to last the required life, according to the specifications laid down. Possible strategies are evaluated for obtaining the optimum by invoking the various decision criteria shown in Fig 4. Each decision criterion has to be quantified and weighted to define a function which can be called a Decision Criteria Index. Such a function is another complex formulation in the system. In the past, this function has always been used in its simplest form, i.e., by subjective evaluation of various factors such as riding quality, safety, and availability of funds.

Evaluation, Storage, and Feedback

Evaluation and feedback are the long-range planned objectives of any management system. A pavement management system involving these fulfills the requirements of a self-sufficient system.

The system's models, when continuously synthesized by feedback from various sources, improve the system and its capabilities. The feedback consists of

(1) analysis of deviations from predicted capabilities,
(2) research investigations, and
(3) sensitivity analysis of the existing system.

A pavement system data bank is an important part of the feedback subsystem. It consists of, among other things, the performance evaluations of the optimal strategies constructed in the past. Data from construction monitoring, measurement of performance over time, and the observation of subsequent expenditures are the important characteristics to be observed from the implemented strategies.

SYSTEMS FORMULATION OF RPS1

Comprehensive formulation of a rigid pavement design system, as discussed above, is the ultimate goal which may be achieved through stages of implementation and feedback as well as additional research. In the systems framework the development of RPS1 can be described by the following terms:

(1) objectives,
(2) inputs,
(3) constraints,
(4) decision criteria,
(5) system analysis, and
(6) output.

Objectives

A large amount of research has been done in the past on various individual models or groups of models defining various parts of the comprehensive system discussed above. A large payoff can be obtained from this research while the ultimate design system and its models are being developed.

Therefore, it was planned to go through the available research literature, analyze the significant models, and formulate the first version of the rigid pavement design system utilizing every model which is available in the existing state-of-the-art and which can be fitted efficiently into the system. It was also desired that such models which are important links in the system and for which the research is not available should be mathematically developed considering their relative importance and time available. Various mathematical models and their development are described in Chapter 4.

The computer program is developed with the following main objectives:

(1) to evolve an efficient solution process,

(2) to serve as a first block in the continuing research, and

(3) to possess an easy and generalized procedure so that future modifications can be incorporated in it with a minimum of effort.

Inputs

System inputs consist of about 115 parameters and are described in Chapter 5. These inputs are dictated by the models used in the system. Enough inputs are provided so that in general

(1) all traffic loads can be accounted for effectively;

(2) existing performance models can be evaluated with the help of the required material properties;

(3) serviceability-age histories can be estimated;

(4) different concretes, subbases, and reinforcements can be tried;

(5) subbases can be effectively designed and evaluated;

(6) joints in initial construction can be designed;

(7) seal coats can be provided where required; and

(8) sufficient maintenance can be provided.

Constraints

Adequate constraints must be provided in the system so that only reasonable amounts of computation time are required for problem solving. This can be accomplished by limiting the number of potentially feasible designs to be analyzed. Three major constraints with respect to the types of designs are built into the system so that it is possible to constrain the system to design one or both types of any of the following items:

(1) pavement types (jointed and continuous),
(2) overlay types (asphalt concrete and portland cement concrete), and
(3) reinforcement types (wire mesh and deformed bars).

Decision Criterion

Minimum total overall cost is selected as the prime decision criterion for the selection of the optimal pavement strategy. Availability of initial funds is another decision criterion and will also act as a restraint. Safety will be controlled by the provision of seal coats and by specifying the minimum serviceability level. Riding quality and maintainability will be controlled also by the minimum specified serviceability level.

For rational economic analysis and decision making in the case of a public enterprise such as a highway, it is desirable that an interest rate be built to properly evaluate the future investments with respect to current revenues. A salvage value of the pavement at the end of the analysis period is also used to enhance the rationalization of economic analysis.

System Analysis

The concepts of stage construction are used for designs which reach the minimum specified serviceability levels at times less than the analysis period. Reinforcement and joints are designed for each initial design. Subbase, concrete, and overlay thicknesses are computed for each strategy designed.

All costs of initial and future construction are calculated. Future costs include those for overlays, maintenance, seal coats, and traffic delays during overlay operation. Initial costs consist of subgrade preparation, subbase, concrete, reinforcement, and joints.

Output

The decision criteria included in the present system are not comprehensive enough to make judgments other than total overall cost. For this reason and others, the designer is presented with a set of alternative designs resulting from various strategies and other pertinent information in the form of a summary table. The most economical design for each pavement-overlay combination and a complete analysis of the number of initial designs, strategies, and relative constraining effects of various restraints are also printed.

For each strategy in the output, a complete description of thicknesses, materials used, overlays, serviceability lives, joint and reinforcement detailing, and each cost involved are printed.

CHAPTER 4. SYSTEM MATHEMATICAL MODELS

The working system RPS1, described in Chapter 5, is developed using various mathematical relationships called systems models. Some of these relationahips exist in the literature and were developed as a result of observations on experimental test roads, laboratory experiments, and other theoretical analyses. Certain other relationships which are deemed necessary for developing a rational working system are derived theoretically by the authors. This chapter describes the developments, assumptions, and limitations of all the models used for RPS1. They are subdivided into the following major categories:

(1) performance models,
(2) models for traffic analysis,
(3) subgrade affected performance models,
(4) foundation strength models,
(5) stochastic variations in the material properties,
(6) models for overlay design,
(7) models for reinforcement design,
(8) economic models, and
(9) miscellaneous.

PERFORMANCE MODELS

The performance model used in this design system originates from the data and results of the AASHO Road Test. The statistical models that were developed and the data used for their development are described in the reports of the AASHO Road Test (Ref 127). The subsequent modifications of these models have been presented in Chapter 2. A thorough understanding of the work done in response to the AASHO Road Test equations and their modifications, the basic assumptions involved, and the validity of the results produced is essential for using the developed models in any kind of a design.

The two modified models (Eqs 2.21 and 2.27) discussed in Chapter 2 encompass the same variables and both can be used for design with the same confidence.

Equation 2.27 is programmed in RPS1 because the slab continuity coefficient J for this equation has been reported in detail (Ref 57). Continuously reinforced concrete pavements can be designed using this equation but with a different value of continuity coefficient J . The model given by Eq 2.21 can also be programmed easily if required.

The design equation 2.27 has been modified for using different concretes, support media strengths, and different load transfer characteristics. Still, it relates specifically to

(1) the environment of the test site and the climatic cycles experienced;

(2) the range in pavement thicknesses, axle loads, and their specific times and rates of aplications;

(3) the construction techniques employed at the Road Test; and

(4) the assumption that E , k , a_1 and f_c have the same effect on load applications carried as varying slab thickness D .

The modified equations are accepted for RPS1 as good approximations. As additional knowledge is obtained, the validity of these approximations will be questioned and improvements will be made. The use of these equations for a design procedure is therefore provisional in nature.

Correction Factor for Age

A life-term factor modifies the AASHO Road Test equations to the form they would have taken had the Road Test pavements (a two-year period of time) been subjected to traffic over a period of time equaling the life of a normal highway pavement under conditions of regular service, i.e., long-time traffic and gradual deterioration from climatic exposure.

The establishment of such a factor was first attempted in Illinois (Refs 17 and 18), an area where physical environment and foundation conditions were similar to the AASHO Road Test conditions and thus could be eliminated as variables. This significant effect of a longer period of service was clearly reflected when actual performance of selected pavements was compared with the performance as predicted by the AASHO Road Test equations.

This comparison led to a factor known as the time-traffic exposure factor T_f , the ratio of the required thickness to the predicted thickness D , both of which are capable of carrying the same traffic loads to the same level of serviceability.

The design term DT in Eqs 2.17 and 2.18 can be modified to be

$$DT = \frac{D}{T_f} + 1 \tag{4.1}$$

The value for T_f was established as 1.3, showing that on the average the performance equation predicted higher levels of performance than could actually be obtained on pavements in regular service.

To account for such an effect, the AASHO Subcommittee for the development of the Interim Design Guide (Ref 68) recommended the use of $.75f_c$ as the working stress in concrete for design by Eq 2.21. This corresponds to reducing the logarithm of the predicted applications by a factor in the range of .924 to .949.

For using Eq 2.27 it was suggested in Ref 57 that the logarithm of predicted applications be multiplied by a factor of .9155.

Though a value of .9155 is used in the present RPS1, it can easily be replaced by the other values for life term as discussed above if they provide a better estimate for this life effect. The Illinois time-traffic exposure factor shows promise of being a better estimate.

MODELS FOR TRAFFIC ANALYSIS

The AASHO Road Test equation pertained to definite identical axle loadings and configurations which traveled on the test sections. Pavements in actual service are not subjected to one type of load but to mixed traffic containing different axle weights and axle configurations loaded to different capacities: above, equal to, or below the legal limits.

An ideal design equation can be obtained by transforming the AASHO Road Test equation to a multiload form so that it includes the effects of magnitudes, configurations, and number of repetitions of various wheel loads as variables. Such an equation is described in Refs 101 and 102 and is very complicated to solve.

The second approach is that of combining the effects of various axle loads into a single summary statistic, for example, the equivalent applications of an 18-kip single axle load. The AASHO Road Test single load equation can be used for computing equivalence factors for transforming the applications of various loads into the equivalent applications of 18-kip single axles. The equivalence factor E_i is a ratio of the 18-kip single axle applications W_{18}

to the number of applications W_i of any other load producing the same amount of distress, i.e., that which brings the pavement to the same level of serviceability index:

$$E_i = \frac{W_{18}}{W_i} \tag{4.2}$$

where W_{18} and W_i are defined by Eqs 2.16 and 2.12 respectively and i represents any axle load.

For RPS1 total equivalent 18-kip axles are determined as

$$W_{tot} = \sum_{i=1}^{j} E_{ic} W_{ic} \tag{4.3}$$

where

W_{ic} = the counted number of axles in the i^{th} category, per day,

E_{ic} = the computed equivalency factor for the i^{th} axle load,

j = the total number of categories of axle loads.

The average number of axles in both directions per day in each category is the input. A category is characterized by a load range with lower and upper values of L_1' and L_2' respectively.

Load L_i', used to determine E_i, is taken as the average of L_1' and L_2':

$$L_i' = \frac{L_1' + L_2'}{2} \tag{4.4}$$

Calculating 18-kip equivalent single axles per day by Eq 4.3, the total number for the entire analysis period W_{AP} is given as

$$W_{AP} = 365 W_{tot} \times D_{fl} \times D_{fd} \left(1 + G_{fa} \times \frac{A_p}{2}\right) \times A_p \tag{4.5}$$

where

A_p = the length of the analysis period,

D_{fd} = the directional distribution factor,

D_{fl} = the lane distribution factor,

G_{fa} = the axle growth rate, per day.

A distribution pattern of total 18-kip axles W_{AP}, calculated above, is developed for use by the Texas Highway Department. The correlation is given below:

$$W_t = W_{AP} \left[A \left(\frac{t}{A_p} \right)^2 + B \left(\frac{t}{A_p} \right) \right] \qquad (4.6)$$

where

W_t = the number of equivalent 18-kip axles experienced by the design facility up to time t,

W_{AP} = the number of equivalent 18-kip axles which will be experienced by the facility for the entire analysis period AP.

A and B are constants:

$$A = \frac{A_p \times G_F}{A_p \times G_F + 2} \qquad (4.7)$$

and

$$B = \frac{2}{A_p \times G_F + 2} \qquad (4.8)$$

where

G_F = the one-direction ADT growth factor per year.

Equation 4.6 is described graphically in Fig 5.

SUBGRADE AFFECTED PERFORMANCE MODELS

Subgrade soils exhibit varying properties with changing physical and environmental conditions. One of the detrimental effects of soils on highway pavements is the producing of differential vertical movements which may decrease the serviceability index by making the pavements rougher.

The vertical movements of soils can be determined with some degree of success by complex theoretical and empirical relationships, but the correlation of the resulting differential movements with the decrease in serviceability of the pavement imposes a very complex problem. The simplest way to consider such effects of soils is to assume a relationship for the loss of serviceability over time. The variables of such a relationship can then be determined by actual observations of pavements over different soils.

Scrivner et al (Ref 104) have presented such a relation in the form of an exponential curve as shown in Fig 6. The curve starts at an initial serviceability index value and is completely defined by the lowest serviceability index it will attain and the rate at which this value will be reached.

The lowest serviceability index, denoted as P_p, is theoretically defined as the ultimate value of serviceability index that a pavement will attain over infinite time when subjected to no traffic or traffic so light that its effect on the pavement can be neglected. The relative rate at which the serviceability index P will approach its ultimate value is called b.

The mathematical form of the relation is derived in terms of a serviceability loss function and is given below:

$$\phi = \phi' (1 - e^{-bt}) \tag{4.9}$$

where ϕ is defined as the serviceability loss function for time t and the corresponding present serviceability index P,

$$\phi = (5 - P)^{0.5} - (5 - P_1)^{0.5} \tag{4.10}$$

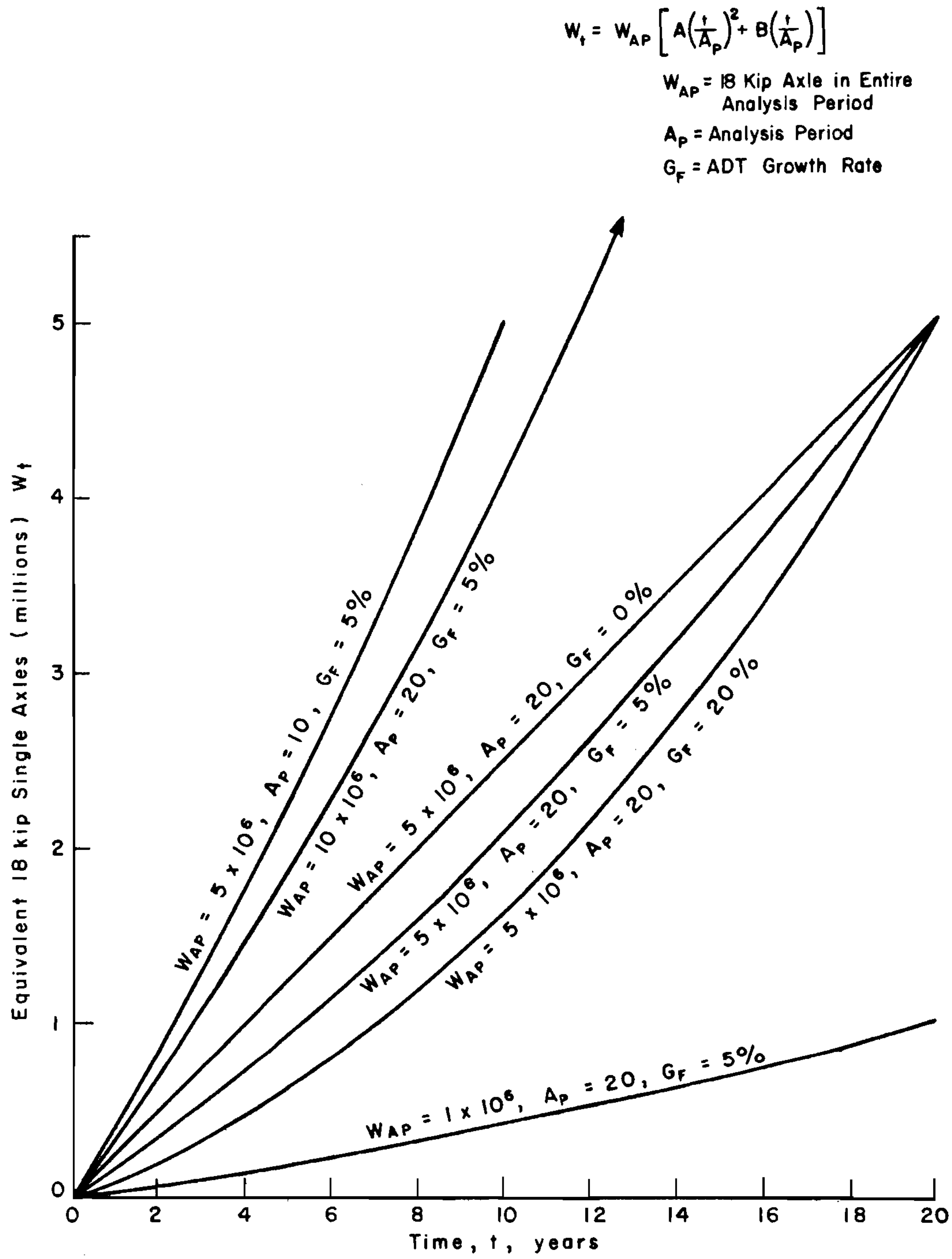


Fig 5. Graphical presentation of the traffic equation (4.6).

$$P = 5 - \left[\sqrt{5-P_i} + \left\{\sqrt{5-P_p} - \sqrt{5-P_i}\right\}\left(1-e^{-bt}\right)\right]^2$$

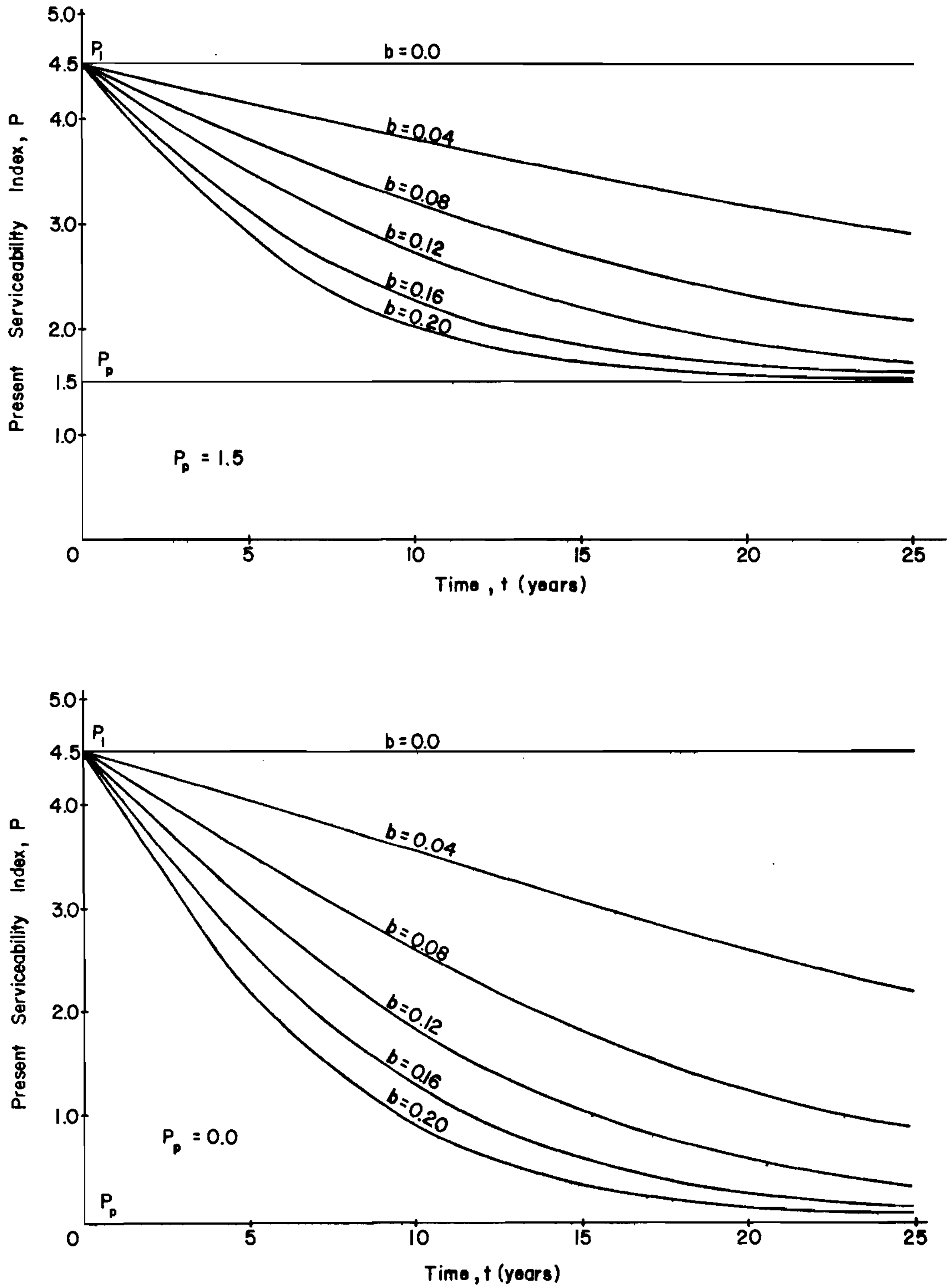


Fig 6. Performance curves for swelling clay effect.

ϕ' is the final value of the serviceability loss function at infinite time when the serviceability index is P_p ,

$$\phi' = (5 - P_p)^{0.5} - (5 - P_1)^{0.5} \tag{4.11}$$

P_1 is the initial value of the serviceability index.

Substituting the values of ϕ and ϕ' in Eq 4.9, P at any time t can be defined as

$$P = 5 - \left[(5 - P_1)^{0.5} + \left\{(5 - P_p)^{0.5} - (5 - P_1)^{0.5}\right\} (1 - e^{-bt})\right] \tag{4.12}$$

If solved for t , the equation yields the form used in RPS1:

$$t = \text{Log}_e \left[\frac{(5 - P_p)^{0.5} - (5 - P_1)^{0.5}}{\left\{(5 - P_p)^{0.5} - (5 - P_1)^{0.5}\right\} - \left\{(5 - P)^{0.5} - (5 - P_1)^{0.5}\right\}} \right]^{1/b} \tag{4.13}$$

The serviceability loss curve due to swelling clay is modified after an overlay construction (Ref 103). Assuming that the slope of the serviceability loss function $\frac{d\phi}{dt}$ remains the same before and after an overlay construction and that the ultimate value of serviceability index P_p remains unchanged, the following new value for b results:

$$b_c = \frac{\phi'_p}{\phi'_c} b_p e^{-b_p t_p} \tag{4.14}$$

where b_c is the new value for b for the present performance period, b_p is the value of b for the previous performance period, ϕ'_p and ϕ'_c are the values of total serviceability loss functions for the previous and the present performance periods respectively, and t_p is the duration of the previous performance period.

FOUNDATION STRENGTH MODELS

The strength of the pavement foundation enters the design equation as a factor k which, as used by Spangler and originally defined by Westergaard (Ref 143), is a linear stiffness constant of an assumed bed of foundation springs. It was assumed that an appropriate value of this modulus k will lead to a sufficiently accurate analysis of the deflections and stresses in pavement slabs.

The value of this empirical constant can generally be improved by providing an intermediate layer of material above the subgrade. This layer under a rigid pavement is called subbase. The improved value of k , according to performance models, reduces the thickness requirement of the concrete slab.

Subbases under rigid pavements are also provided for other functions such as to provide a uniform and stable support for the concrete slab, to minimize the effects of volume changes of subgrades, and to prevent pumping. These improvements tend to increase the performance of concrete pavements throughout their lifetime of service.

The theoretical increase in the lives of pavements as calculated by the performance equation is analyzed in light of the economics in RPS1. The improvement in the value of modulus k is determined by the models developed using elastic layered theory. The statistical equations or models are developed to simulate the results given by elastic layer theory. The procedure for developing these models is presented in Appendix 6A. The models are built into the computer program and the program user may avoid the details of the development or the models.

Three prediction models are developed and used in RPS1. The following are the relationships along with the transformations used for the analysis.

Subbase thickness 0-6 inches:

$$
\begin{aligned}
K_T = {} & 385.76 + 69.7\tau_1 + 8.59\tau_2 + 27.06\varepsilon_1 + 3.98\varepsilon_2 + 5.55\varepsilon_3 \\
& + 66.48M_1 - 1.6M_2 + 0.43M_3 + 31.07\tau_1\varepsilon_1 + 4.41\tau_1\varepsilon_2 + 5.06\tau_1\varepsilon_3 \\
& + 7.08\tau_1 M_1 - 2.35\tau_1 M_2 + 0.25\tau_1 M_3 + 4.01\tau_2\varepsilon_1 + 0.42\tau_2\varepsilon_2 \\
& + 1.13\tau_2 M_1 + 3.56\varepsilon_1 M_1 + 0.36\varepsilon_2 M_1 - 0.20\varepsilon_2 M_2 + 1.06\varepsilon_3 M_1
\end{aligned}
$$

$$+ 4.22\tau_1\epsilon_1M_1 - 0.46\tau_1\epsilon_1M_2 + 0.47\tau_1\epsilon_2M_1 - 0.18\tau_1\epsilon_2M_2$$

$$+ 0.66\tau_2\epsilon_1M_1 + 0.11\tau_2\epsilon_2M_1 + 0.13\epsilon_1M_3 + 0.14\tau_1\epsilon_1M_3 \qquad (4.15)$$

Subbase thickness 6-12 inches:

$$K_T = 578.62 + 115.16\tau_1 + 0.59\tau_2 + 108.03\epsilon_1 + 13.39\epsilon_2 + 13.09\epsilon_3$$

$$+ 88.40M_1 - 7.09M_2 + 1.35M_3 + 45.94\tau_1\epsilon_1 + 4.57\tau_1\epsilon_2 + 2.92\tau_1\epsilon_3$$

$$+ 13.81\tau_1M_1 - 3.00\tau_1M_2 + 0.58\tau_1M_3 + 15.36\epsilon_1M_1 - 1.46\epsilon_1M_2$$

$$+ 0.40\epsilon_1M_3 + 1.55\epsilon_2M_1 - 0.45\epsilon_2M_2 + 0.07\epsilon_2M_3 + 2.36\epsilon_3M_1$$

$$+ 6.93\tau_1\epsilon_1M_1 - 0.56\tau_1\epsilon_1M_2 + 0.13\tau_1\epsilon_1M_3 + 0.61\tau_1\epsilon_2M_1$$

$$- 0.10\tau_1\epsilon_2M_2 \qquad (4.16)$$

Subbase thickness 12-18 inches:

$$K_T = 810.62 + 115.99\tau_1 + 200.53\epsilon_1 + 23.21\epsilon_2 + 18.75\epsilon_3 + 116.50M_1$$

$$- 13.39M_2 + 2.66M_3 + 46.54\tau_1\epsilon_1 + 5.35\tau_1\epsilon_2 + 2.75\tau_1\epsilon_3 + 14.19\tau_1M_1$$

$$- 3.30\tau_1M_2 + 0.71\tau_1M_3 + 29.35\epsilon_1M_1 - 2.94\epsilon_1M_2 + 0.74\epsilon_1M_3$$

$$+ 3.00\epsilon_2M_1 - 0.72\epsilon_2M_2 + 0.17\epsilon_2M_3 + 3.19\epsilon_3M_1 - 0.54\epsilon_3M_2$$

$$+ 7.08\tau_1\epsilon_1M_1 - 0.92\tau_1\epsilon_1M_2 + 0.20\tau_1\epsilon_1M_3 + 0.88\tau_1\epsilon_2M_1$$

$$- 0.17\tau_1\epsilon_2M_2 \qquad (4.17)$$

Transformations are defined as

$$\epsilon_1 = \frac{\mathrm{Log}_{10}E_3 - 5.05}{0.35} \qquad (4.18a)$$

$$\epsilon_2 = \epsilon_1^{\,2} - 4 \qquad (4.18b)$$

$$\epsilon_3 = \frac{\epsilon_1^{\,3} - 7\epsilon_1}{6} \qquad (4.18c)$$

$$M_1 = \frac{E_4 - 8100}{1500} \qquad (4.18d)$$

$$M_2 = \frac{3M_1^{\,2} - 35}{8} \qquad (4.18e)$$

$$M_3 = \frac{5M_1^{\,3} - 101M_1}{24} \qquad (4.18f)$$

τ_1 and τ_2 are different for the three equations.
For 0-6 inches:

$$\tau_1 = \frac{D_3 - 3}{3} \qquad (4.19a)$$

$$\tau_2 = 3\tau_1^{\,2} - 2 \qquad (4.19b)$$

For 6-12 inches:

$$\tau_1 = \frac{D_3 - 9}{3} \qquad (4.20a)$$

$$\tau_2 = 3\tau_1^{\,2} - 2 \qquad (4.20b)$$

For 12-18 inches:

$$\tau_1 = \frac{D_3 - 15}{3} \qquad (4.21a)$$

$$\tau_2 = 3\tau_1^2 - 2 \qquad (4.21b)$$

D_3 , E_3 , and E_4 are defined in Appendix 6A.

For each of these equations the values of correlation coefficient R^2 and the standard error of residuals are given below:

	Standard Error	R^2
Equation, 0-6 inches	3.752	.9998
Equation, 6-12 inches	3.797	.9999
Equation, 12-18 inches	7.178	.9998

The value of the modulus as determined above is liable to variations due to the instability caused by traffic and environmental factors during the lifetime of the pavement. Erosion, pumping, repetitive loadings, and freeze and thaw are detrimental parameters which result in a system's loss of integrity and support media strength.

Susceptible soils (generally fine-grained) go into suspension in the free water if present immediately below the pavement and are pumped out along the edges and joints by repetitive deflections of the slab due to the wheel loads. The phenomenon is characterized as "pavement pumping" and results in void spaces of varying sizes along the edges and the joints.

Models to quantify the loss of support due to the above factors and their effects on performance have never been attempted. For rigid pavement system, a model is developed for this purpose using numerical solutions for stresses in plates. The details of development are given in Appendix 6B. The model developed is given below.

$$\text{Log}_{10} k_M = 1.685 - 0.21E_f' + 0.007\ E_f'' + 0.023E_f''' + 0.081k_t'$$

$$+ 0.005k_t'' + 0.002k_t''' - 0.01E_f'k_t' - 0.002E_f'k_t'' - 0.006E_f''k_t'$$

$$- 0.005E_f''k_t'' + 0.006E_f'''k_t' + 0.004E_f'''k_t'' + 0.001E_f'''k_t'''$$

$$- 0.002E_f''k_t''' - 0.0004E_f'k_t''' \tag{4.22}$$

Polynomial regression transformations are

$$E_f' = \frac{E_f - 1.5}{2} \tag{4.23a}$$

$$E_f'' = \frac{E_f'^2 - 5}{4} \tag{4.23b}$$

$$E_f''' = \frac{5E_f'^3 - 41E_f'}{12} \tag{4.23c}$$

$$k_t' = 10\ (\mathrm{Log}_{10}k_T - 2.3) \tag{4.23d}$$

$$k_t'' = \frac{k_t'^2 - 21}{4} \tag{4.23e}$$

$$k_t''' = \frac{k_t'^3 - 37k_t'}{12} \tag{4.23f}$$

k_M , k_T , and E_f are defined in Appendix 6B.

Figure 7 describes the model graphically. The value k_T as given on the abscissa, with an erodability factor E_f , modifies to a value k_M , as given on the ordinate.

This is the first attempt to quantify the effects of this particular kind of deterioration. For simplification, slab dimensions, load intensities, and certain other parameters are held constant. Values given to them are based on engineering judgment. As additional knowledge is obtained through

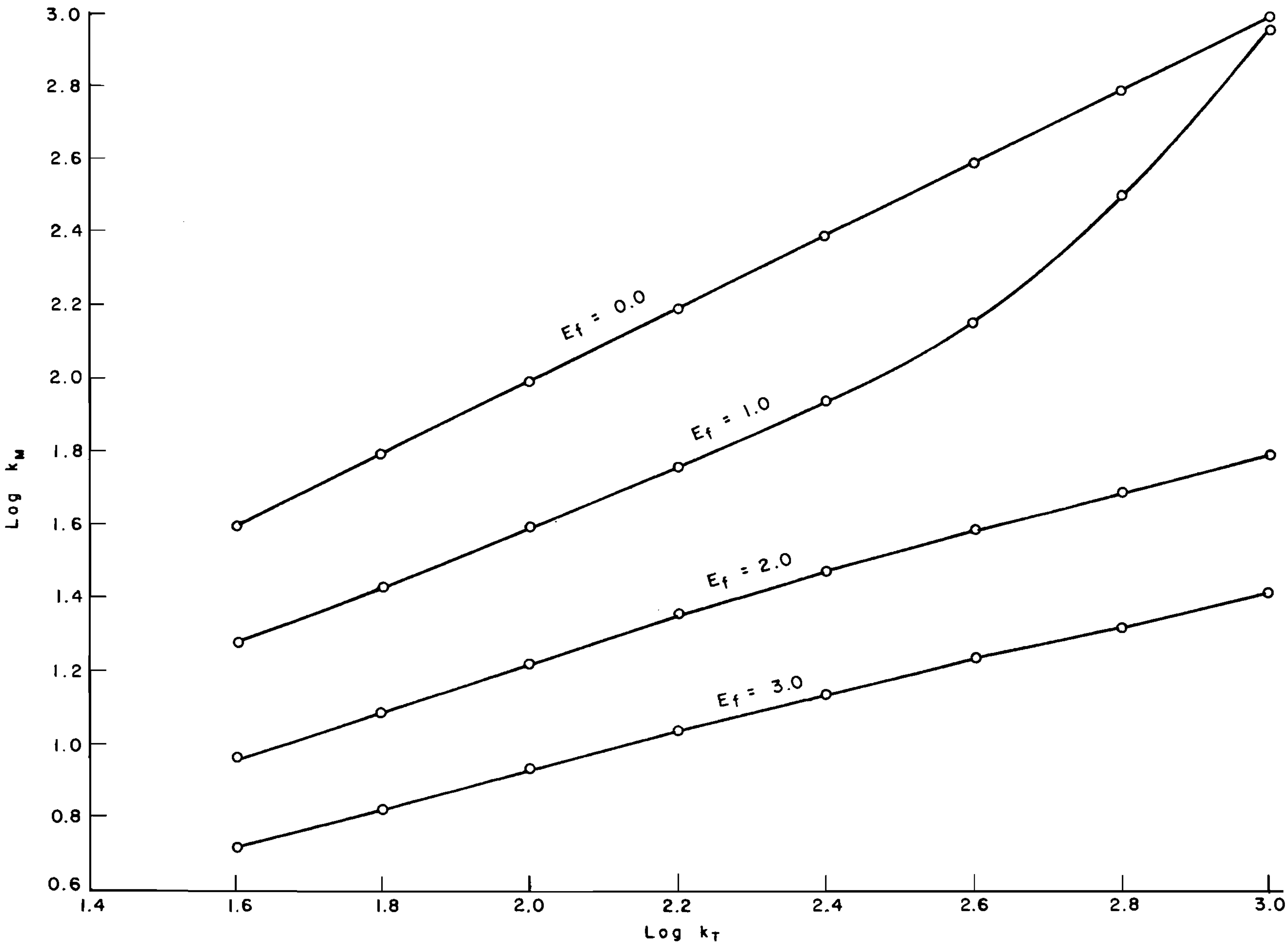


Fig 7. Reduced support value k_M as given by initial value k_T and erodability factor E_f .

further research, the validity of this approach will be improved and the models presented above will be verified or modified.

STOCHASTIC VARIATIONS IN THE MATERIAL PROPERTIES

In RPS1, probability is applied in computing the design values of the following variables:

(1) flexural strength of concrete,
(2) modulus of subgrade reaction, and
(3) Texas triaxial class of the subgrade.

It is assumed that these properties in a large population of samples, if plotted against percentages of occurrences, will fall along a continuous probability distribution defined by a normal curve.

For this type of data, the probability that x will assume a value between x and $x + dx$ is given by dP as

$$dP = \frac{1}{\alpha\sqrt{2\pi}} e - \frac{(x - \overline{\mu})^2}{2\alpha^2} dx \qquad (4.24)$$

where $\overline{\mu}$ and α are, respectively, the universe mean and standard deviation. The integral of the above equation over all values of x is equal to unity. This integral can be solved by using an inverse error function subroutine in the computer. However, for RPS1 the following procedure for solution is adopted.

A value A is determined based on the confidence level V_c specified in the input:

$$A = \frac{50 - V_c}{100} \qquad (4.25)$$

The absolute value of A is the area under the normal curve from the mean value V_m to the design value V_d to be computed. The values of z corresponding to the values of A are built in RPS1 in data arrays where

$$z = \frac{V_d - V_m}{\alpha} \tag{4.26}$$

A value of z corresponding to the value of A determined above gives the design value of the variable as

$$V_d = V_m + \alpha z \tag{4.27a}$$

or

$$V_d = V_m - \alpha z \tag{4.27b}$$

according to whether A is +ve or -ve .
The limits are $0 \leq z \leq 3.9$ for $0.0 \leq A \leq 0.5$.

MODELS FOR OVERLAY DESIGN

Overlays for rehabilitation of existing highway pavements are generally designed by evaluating the in-place load-carrying capacities of existing structures. Major procedures followed to evaluate the existing pavement structures are

(1) deflection measurements,
(2) assigning strength coefficients to the various layers,
(3) estimation or determination of properties of layer materials, and
(4) condition surveys.

RPS1, which formulates the alternative strategies by using the concepts of stage construction and relative economy, needs the prediction of would-be in-place evaluations of the pavement structures overlayed at any time after the initial construction. Different procedures available and the ones used for RPS1 will be discussed under two categories:

(1) asphalt concrete overlays and
(2) portland cement concrete overlays.

Asphalt Concrete Overlays

Asphalt concrete overlays over rigid pavements may be designed by any of the procedures given below:

(1) using the AASHO model for flexible pavements as reported in the Interim Guide (Ref 61),

(2) using the deflection based model for flexible pavements as developed by Scrivner et al (Ref 104), and

(3) using the Corps of Engineers' empirical equation for the design of flexible overlays over rigid pavements (Ref 32).

The above given methods have certain drawbacks. The AASHO model requires the use of material coefficients for the layers. The values of these coefficients can at best be the designer's estimates in the present state of knowledge. The deflection based model has more applicability in that the coefficients used in the model can be quantitatively determined by Dynaflect data (Ref 105) on similar existing pavements. However, both the mothods are questionable extrapolations of the empirical equations derived for the design of flexible pavements. The Corps of Engineers' empirical formula involves the use of a factor related to the condition of the pavement at the time of overlay. This factor is again not quantified properly and its value is mainly based on the designer's estimate.

In view of the difficulties encountered in the use of the above given models, a new model for the design of asphalt concrete overlay is developed using layered elastic theory. The details of the method adopted for developing the model are given in Appendix 6C. The details of the model and its development are rather involved, and it is not necessary for a program user to go through them. Layer elastic theory was used to develop this model.

The thickness of the composite pavement, consisting of existing concrete thickness D_2 and the asphalt concrete overlay thickness D_1, is theoretically replaced by a concrete thickness D, which is evaluated in analysis by the extended AASHO model (Ref 57) for the design of rigid pavements. The model is given as

$$D = 11.77 + 0.8E_{\ell} - 0.06E_q + 0.93D_{\ell} + 0.03D_q + 0.55K_{\ell} + 0.12K_q$$

$$- 0.02E_\ell D_\ell - 0.16E_\ell K_\ell - 0.03E_\ell K_q + 0.007E_q D_\ell + 0.01E_q K_\ell$$

$$- 0.03D_\ell K_\ell - 0.02D_\ell K_q + 0.04D_q K_\ell + 0.01D_q K_q + 0.02E_\ell D_\ell K_\ell$$

$$+ 0.008E_\ell D_\ell K_q - 0.02E_\ell D_q K_\ell + 1.51T_\ell + 0.11T_q - 0.02T_c$$

$$+ 0.43T_\ell E_\ell - 0.04T_\ell E_q - 0.04T_\ell D_\ell + 0.01T_\ell D_q + 0.008T_\ell E_\ell D_\ell K_\ell$$

$$+ 0.26T_\ell K_\ell + 0.05T_\ell K_q + 0.02T_q E_\ell - 0.008T_q E_q - 0.005T_q D_\ell$$

$$- 0.02T_q K_\ell - 0.01T_c E_\ell - 0.009T_\ell E_\ell D_\ell - 0.09T_\ell E_\ell K_\ell - 0.02T_\ell E_\ell K_q$$

$$+ 0.004T_\ell E_q D_\ell - 0.009T_\ell D_\ell K_\ell - 0.009T_\ell D_\ell K_q \tag{4.28}$$

The transformations are

$$E_\ell = \frac{E_1 - 45{,}000}{350{,}000} \tag{4.29a}$$

$$E_q = 3E_\ell^{\,2} - 2 \tag{4.29b}$$

$$D_\ell = D_2 - 9 \tag{4.29c}$$

$$D_q = \frac{D_\ell^{\,2} - 5}{4} \tag{4.29d}$$

$$K_\ell = \frac{\mathrm{Log}_{10}\, k_M - 2.301}{0.699} \tag{4.29e}$$

$$K_q = 3K_\ell^{\,2} - 2 \tag{4.29f}$$

$$T_\ell = \frac{D_1 - 6}{3} \tag{4.29g}$$

$$T_q = T_\ell^2 - 2 \tag{4.29h}$$

$$T_c = \frac{5T_\ell^3 - 17T_\ell}{6} \tag{4.29i}$$

k_M is the modified value of modulus of support reaction at the top of the subbase, and E_1 is the asphalt concrete modulus value. The prediction equation has a correlation coefficient R^2 of 0.9998.

The performance of the equivalent thickness determined by the above model and analyzed by the extended rigid pavement design equation (Eq 2.27) is compared with the AASHO flexible pavement design model (Ref 61) to gain confidence in the new concept. Comparisons are shown in Fig 8.

Portland Cement Concrete Overlays

These overlays have not been frequently used in the past, and not much is reported in the literature about their design. A rational design method should obviously consider factors such as fatigue of concrete, volume change stresses, and reflection cracking. The Corps of Engineers (Refs 2 and 31) has reported an empirical equation for the design of such overlays, primarily for airfield pavements. The equation is used in RPS1 and is given as

$$D = \sqrt[1.4]{C_D h_e^{1.4} + h_o^{1.4}} \tag{4.30}$$

where D is concrete thickness which can be replaced for existing concrete thickness h_e plus a concrete overlay thickness h_o . C_D is a coefficient determined by the condition of the existing pavement at the time of the overlay.

The value of C_D generally varies between 0.35 and 1.0 for badly cracked slabs and slabs in excellent condition, respectively. A slight variation of this coefficient produces considerable differences in computed thickness D . For example, a difference of 0.1 in the value of C_D for an 8-inch existing

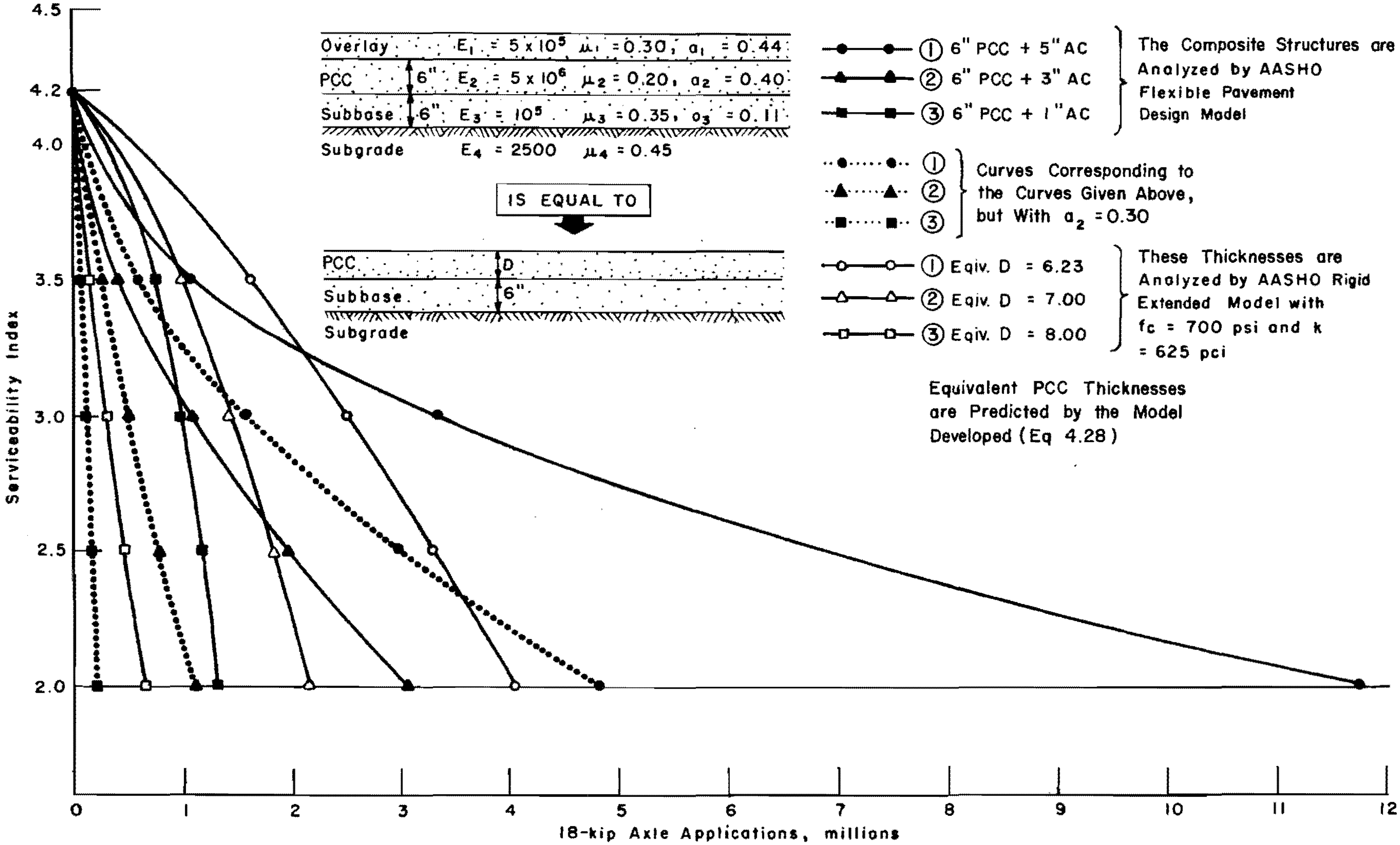


Fig 8. Comparison of AASHO flexible model (used for overlays) with modified AASHO rigid model (used for equivalent concrete thicknesses).

pavement produces an average error of 0.63 inches in computed overlay thickness (Ref 78). The coefficient can be qualitatively associated with the amount of cracking observed on existing slabs, other fatigue considerations, or engineering judgment. Fig 9 graphically describes this model for two extreme values of C_D.

MODELS FOR REINFORCEMENT DESIGN

Reinforcement is designed in RPS1 for controlling crack widths produced by tensile stresses due to volume changes in concrete slabs in horizontal directions. Since the magnitude of such tensile stresses is dependent upon the free length of the slab, different models for reinforcement design apply to jointed and continuously reinforced pavements. The underlying basic theory for design, however, remains the same for both types.

Total resistance to the horizontal movement of the slab on partially elastic support may be considered to be due to three factors:

(1) resistance due to elastic deformation of the support,
(2) resistance due to inelastic deformation of the support, and
(3) resistance due to sliding friction.

At the lowest temperature, the slab ceases to shorten, and since the horizontal movement ceases, the stress due to inelastic deformation and frictional resistance vanishes. The volume change stresses, therefore, are most critical in a state of continuously decreasing temperature when all three stress producing factors are active.

If the slab displacement is small only the resistance to elastic deformation can be developed, but in cases of large displacements all three resistances can be active. The magnitude of the coefficient of resistance at each horizontal increment of slab length or width is dependent upon the horizontal displacement of the increment.

In a pavement slab the total displacement due to contraction increases at a nearly uniform rate from zero at the center line to the maximum at the end of the slab. Thus, the developed coefficient of support resistance has a zero value at the center of the slab, and as the distance from the center of the slab is gradually increased the corresponding coefficient of resistance also increases until a point is reached where the coefficient reaches a maximum and a constant value.

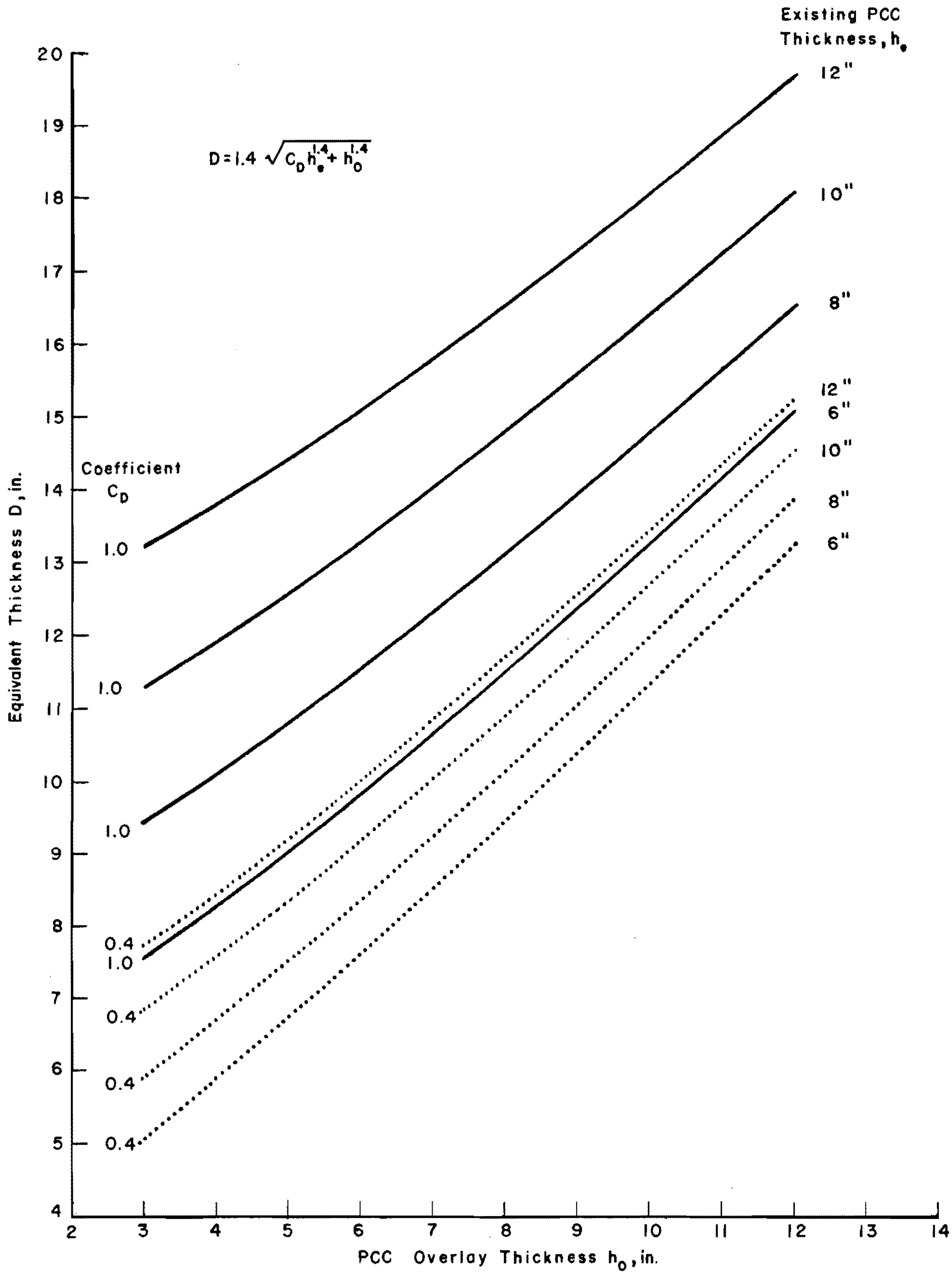


Fig 9. Effective concrete thicknesses by Corps of Engineers equation (partially bonded PCC overlays), Eq 4.30.

In the proposed models an average value of this coefficient of resistance applied over the entire area of the slab is used for the computation of maximum contraction stresses. The exact distribution and the procedure to calculate the average value of the coefficient of resistance from its maximum value can be found in Ref 65.

Longitudinal steel in jointed concrete pavements is designed by the following model:

$$A_s = \frac{D\, w_c\, L_d\, F_a}{24 f_s} \qquad (4.31)$$

where

A_s = cross-sectional area of steel in square inches per foot of slab width;

D = the thickness of concrete, inches;

w_c = weight of concrete, pounds per cubic foot;

L_d = distance between free transverse joints, feet;

F_a = average value of coefficient of support resistance;

f_s = allowable unit stress in reinforcement, psi.

Since the total cost of transverse joints decreases as the required amount of steel increases, RPS1 optimizes the area of steel to give minimum total cost of joints and reinforcement.

Longitudinal reinforcement for continuously reinforced pavements is designed by considering the pavement as a continuous, restrained member. The model used in RPS1 is taken from the final report of NCHRP Project 1-11 (Ref 77) and is given below:

$$A_s = 12D(1.3 - 0.2F_a)\,\frac{T_s}{f_s} \qquad (4.32)$$

where T_s is the tensile strength of concrete, in psi. Other terms are as previously defined.

Transverse reinforcement in both types of pavements is designed by the model given in Eq 4.31 with the value of L_d redefined to be the free width of the pavement. The area of steel required for tie bars across the longitudinal joint is taken to be equal to the area of transverse reinforcement calculated at that section.

If the reinforcement is to hold the cracks in a tightly closed condition, its elongation at cracks should be limited to small amounts. The total elongation of steel is dependent on the length that is free to elongate, and this free length is created when the bond is destroyed over a certain length of steel at a crack. Since the length over which the bond is destroyed remains unknown, it is not possible to compute accurately the total elongation corresponding to a given stress. This, in turn, makes it rather impossible to specify an allowable steel stress that will insure the maintenance of tightly closed cracks. With this uncertainty in view, a safety factor is specified in RPS1 with respect to steel stress. The working stress is taken to be 0.75 times the yield point strength. Minimum area of steel in continuously reinforced pavements is specified to be 0.4 percent because experience has shown that the continuity condition across transverse cracks is lost when the percentage of steel decreases below this value (Ref 76).

ECONOMIC MODELS

Systems analysis results in alternate strategies which are compared and optimized in RPS1 by the single decision criterion of overall costs of the strategies. Each strategy consists of a variety of expenses incurred at different times during the design life. Relative comparisons, therefore, are made with all future costs discounted back to present value. The interest rate for this purpose is input by the program user.

Future costs are discounted to the present worth by a compound interest model. For example, the present worth C_p at interest rate I_r of a future cost C_f incurred after t years will be

$$C_p = \frac{C_f}{(1 + I_r)^t} \qquad (4.33)$$

Pavement investment can be divided into three main categories:

(1) initial costs,
(2) future costs, and
(3) salvage returns.

Total overall cost is therefore given by

$$C_t = C_i + C_{pf} - C_{sal} \tag{4.34}$$

where

C_i = the cost of initial construction,

C_{pf} = the summation of present worth of all future costs incurred for a strategy,

C_{sal} = the salvage return discounted to its present value, and

C_t = the total cost.

Initial Costs

Initial costs consist of the expenses for initial design. These expenses are

(1) cost of subgrade preparation C_{sp} ,
(2) cost of in-place concrete C_c ,
(3) cost of in-place subbase C_s ,
(4) cost of reinforcement C_r , and
(5) cost of joints C_j .

Thus

$$C_i = C_{sp} + C_c + C_s + C_r + C_j \tag{4.35}$$

The cost of subgrade preparation C_{sp} consists of the costs of scarification and mechanical or chemical stabilization per square yard of subgrade surface.

The in-place cost of concrete C_c is the sum of three different cost inputs.

$$C_c = C_{ce} + C_{cu} + C_{cs} \tag{4.36}$$

where

C_{ce} = the initial cost of mixing and hauling equipment as well as labor for pouring concrete, per square yard of the pavement;

C_{cu} = the cost per square yard of concrete in the pavement; and

C_{cs} = the cost of curing, finishing, and surfacing the concrete, per square yard of the pavement.

In-place cost of subbase C_s is the sum of two different costs:

$$C_s = C_{se} + C_{su} \tag{4.37}$$

where

C_{se} = the cost of mixing, hauling, and compaction equipment as well as the cost of labor, per square yard of the pavement; and

C_{su} = the cost per square yard of subbase in the pavement.

Cost of reinforcement C_r is the sum of three different costs:

$$C_r = C_{rl} + C_{rt} + C_{rb} \tag{4.38}$$

where

C_{rl} = the cost of longitudinal reinforcement,

C_{rt} = the cost of transverse reinforcement, and

C_{rb} = the cost of tie bars provided in the longitudinal joints.

Cost of reinforcement is computed by the areas of steels designed for the section:

$$C_{rl} = 30.625\ A_{rl} \times C_{sl} \tag{4.39}$$

$$C_{rt} = 30.625\ A_{rt} \times C_{st} \tag{4.40}$$

where A_{rl} and A_{rt} are respectively the required areas per foot width of longitudinal and transverse steels, in square inches, and C_{sl} and C_{st} are respectively the costs of longitudinal and transverse steels, in dollars per pound.

$$C_{rb} = \frac{153.13\ D_{rb}\ A_{rb}\ N_{jl}\ C_{Sb}}{B} \tag{4.41}$$

where

A_{rb} = the area of tie bars required per foot length of the longitudinal joint;

D_{rb} = the diameter of tie bars used, inches;

N_{jl} = the number of longitudinal joints provided in the pavement;

B = the total width of pavement, feet; and

C_{sb} = the cost of tie bar steel, dollar per pound.

C_{rl} , C_{rt} , and C_{rb} are costs computed per square yard of the pavement. Steels are assumed to weigh 490 pounds per cubic feet. Lengths of tie bars are assumed to be 60 times the diameter of the bars provided.

Cost of joints C_j is the sum of two costs:

$$C_j = C_{jl} + C_{jt} \tag{4.42}$$

where C_{jl} and C_{jt} are respectively the costs of longitudinal and transverse joints per square yard of pavement.

$$C_j = 9\left[\frac{N_{jl} \cdot C_{lf}}{B} + \frac{C_{tf}}{S_{jt}}\right] \tag{4.43}$$

where

C_{lf} = cost per foot of longitudinal joint excluding the cost of tie bars;

C_{tf} = cost per foot of transverse joint including dowels, sawing and sealing, etc.; and

S_{jt} = computed spacing of transverse joints in feet.

Future Costs

The expenses subsequent to the initial construction are accumulated throughout the analysis period. These expenses are

(1) present worth of the overlays C_o ,
(2) present worth of the maintenance C_{mt} , and
(3) present worth of the seal coats C_{sc} .

Thus, the present value of all future costs C_{pf} is given as

$$C_{pf} = C_o + C_{mt} + C_{sc} \tag{4.44}$$

C_{pf} , C_o , C_{mt} , C_{sc} are costs computed per square yard of the pavement.

Cost of Overlays. There are two specific aspects of overlay cost analysis:

(1) overlay construction cost C_{oc} , and
(2) traffic delay cost during overlay operations C_{od} .

Overlay construction cost is the present worth of all future overlays. For asphalt concrete overlays C_{oc} is computed as

$$C_{oc} = \sum_{n=1}^{N} \frac{T_n \cdot C_a + C_{ae}}{36(1 + I_r)^{t_n}} \tag{4.45}$$

where

T_n = thickness, in inches, of n^{th} overlay;

t_n = time, in years, when n^{th} overlay is provided;

C_a = cost per cubic yard of compacted asphalt concrete overlay;

C_{ae} = cost per square yard of equipment, labor and other charges; and

N = number of overlays computed for design strategy.

Cost analysis of PCC overlays is the same as that of concrete in the original PCC pavement (Eq 4.36). The model is

$$C_{oc} = \sum_{n=1}^{N} \frac{T_n \cdot C_{cc} + C_{ce} + C_{cs}}{(1 + I_r)^{t_n}} \tag{4.46}$$

where C_{cc} is cost per cubic yard of PCC provided in the overlay and all other terms are as previously defined.

Traffic delay cost during overlay construction deals with indirect costs which an overlay operation will incur due to the disturbances it produces in traffic flow. Speed fluctuations and delays caused thereby give rise to these costs.

The following basic types of delays and time losses are considered during the overlay operations:

(1) having to stop outside the restricted area because of congestion,

(2) having to stop in a restricted area because of the movement of personnel and equipment, and

(3) having to travel at a reduced speed in the restricted area.

The following basic costs are calculated for traffic delay:

(1) excess time and operating cost due to the cycles of reducing from a particular speed to a stop and returning to that speed,

(2) excess time and operating (idling) cost due to being stopped,

(3) excess time and operating cost due to a cycle of reducing from the approach speed to the through speed and returning to the approach speed, and

(4) excess time and operating cost due to traveling a certain distance at a reduced speed instead of the approach speed.

The first two kinds of costs occur

(1) outside the restricted area due to congestion when hourly traffic input into the area is greater than the output from the area and therefore a certain amount of traffic is stopped, and

(2) inside the restricted area when the vehicles have to be stopped because of the movement of overlay equipment and personnel.

The excess time and operating cost of slowing or stopping from different speeds and traveling at reduced uniform speeds and the costs of idling are calculated in RPS1 by the tables in the form of data arrays. The tables for these costs are taken from Ref 104. The original sources of information are Refs 1, 44, 112, 123, 134, and 148. The procedure and models for traffic delay costs are described in Appendix 7.

Total traffic delay cost of all overlays discounted to the present worth C_{od} per square yard of pavement is given by

$$C_{od} = \sum_{n=1}^{N} \frac{C_n}{(1 + I_r)^{t_n}} \tag{4.47}$$

where

N = number of overlays computed for the design strategy;

I_r = interest rate;

t_n = time, in years, when n^{th} overlay is provided;

C_n = total cost of traffic delay per square yard of pavement during the construction of n^{th} overlay as determined in Appendix 7.

Cost of Maintenance. NCHRP Report 42 (Ref 62) describes a comprehensive nationwide study undertaken to quantify maintenance requirements on interstate highways. Twenty-eight test sections were selected in five states: New York, Florida, Ohio, Texas, and California. Different maintenance cost requirements were compiled for a period of 12 months on these sections. A regression analysis of data with respect to maintenance requirements for pavement and shoulders gave the following model:

$$U_m = 19.72\,X_1^2 + 13.72\,X_2 - 183 \tag{4.48}$$

where

U_m = yearly pavement and maintenance requirement units for a centerline mile of four-lane interstate highway or its equivalent in interchanges or its equivalent in multilane pavements,

X_1 = age of pavement in years after initial or an overlay construction up to the beginning of the year for which U_m is calculated,

X_2 = number of days in a year when the maximum daily temperature is below 32° F.

The requirement units U_m include comparable units of labor, equipment, and materials. The total units are divided into quantities of each component by the factors based on average distribution of these components. The factors are

	Urban Areas	Rural Areas
Labor	60%	44%
Equipment	19%	21%
Material	21%	35%

The units can be interpreted directly as dollars if the following conversion rates, as assumed in regression analysis, are used:

Composite labor rate = \$2.20 per maintenance unit

Composite equipment rental rate = \$2.72 per maintenance unit

Material cost = \$1.00 per maintenance unit.

The original report should be referred to for definitions of "Composite" values. The above rates are averages of the values determined for the five states. The values considered in the analysis for labor, equipment, and materials for the State of Texas are respectively \$1.98, \$2.66, and \$1.00. In RPS1 maintenance, the model uses any values for these rates specified by the designer.

There are accuracy limitations on the model developed because of relatively small samples taken in five states over a single year. On the other hand, it should be noted that the State of Texas had six sections in an analysis of a total of 28 test sections. The sections in Texas were spread throughout the state.

The model is reported to be best suited for large segments of the interstate system and should be modified for other types of highways. The prediction accuracy of the model with respect to the original data is an overall difference of 0.85 percent.

Assuming that each year's maintenance cost calculated by the model is paid at the beginning of the year, the total discounted maintenance cost for a strategy is given as

$$C_{mt} = \sum_{j=1}^{J} \left[\sum_{\ell=1}^{L_j} \frac{C_{\ell,j}}{\left(1 + I_r\right)^{N_j + \ell - 1}} + \frac{C_{L_j + 1,j}}{\left(1 + I_r\right)^{N_j + L_j}} \left(L_j' - L_j \right) \right] \tag{4.49}$$

where

$$N_j = \sum_{k=1}^{j} L_{k-1}'$$

$$L_o' = 0.0$$

$$L_j' = A_p - N_j$$

The quantities are defined as

ℓ = year number after initial or overlay construction for which $C_{\ell,j}$ is calculated;

$C_{\ell,j}$ = cost of maintenance for ℓ^{th} year in j^{th} performance period after initial or an overlay construction, per square yard of pavement;

L_j = value of L'_j in j^{th} performance period, rounded off to the lower whole number;

L'_j = life of the j^{th} performance period;

j = performance period number;

J = total number of performance periods within the analysis period;

A_p = analysis period; and

I_r = interest rate.

Cost of Seal Coats. Seal coats in RPS1 are provided for strategies where asphalt concrete overlays are provided. The time to the first seal coat after an overlay and the time between consecutive seal coats within the same performance period are specified by the designer along with the cost of one seal coat per lane mile.

If J_k number of seal coats are provided in the k^{th} performance period and if the cost per square yard of one seal coat is given by C_{one} , the present worth of all seal coats provided on a strategy will be

$$C_{sc} = \sum_{k=2}^{K} \sum_{j=1}^{J_k} \frac{C_{one}}{(1 + I_r)^{t_{jk}}} \tag{4.50}$$

where

K = total number of performance periods for a strategy, with the last performance period ending with the end of the analysis period, and

t_{jk} = time when the particular seal coat is provided after the initial construction.

The number of seal coats and their schedules in a performance period are calculated by simple additions.

Salvage Returns

The salvage returns of a pavement are the values of usable materials at the time when pavement is abandoned. Since the utility of pavement materials when abandoned cannot be generalized and depends upon circumstances at that time, a salvage percentage is built into the program, to be specified by the user.

The salvage percent P_{sv} is defined as the returns in percent of the cost of initial and overlay materials provided in the pavement.

The present worth of salvage returns as calculated in RPS1 is

$$C_{sal} = \left(T_{cc} \cdot C_{cy} + T_{ov} \cdot C_{oy}\right) \frac{P_{sv}}{3600(1 + I_r)^{A_p}} \qquad (4.51)$$

where

T_{cc} = thickness of concrete, inches;

C_{cy} = cost of concrete per cubic yard in the pavement;

T_{ov} = total thickness of all overlays during the life of the pavement, inches;

C_{oy} = cost of overlay material per cubic yard in the pavement; and

A_p = analysis period, years.

MISCELLANEOUS

Certain models used in RPS1 do not fall in any of the categories described previously. They are given here.

Simultaneous Solution of Equations

Finding the life of a pavement structure requires the simultaneous solution of the three equations described earlier. They are the performance equation (Eq 2.27), the traffic equation (Eq 4.6), and the swelling clay equation (Eq 4.13). The three equations can be written as shown below.

Performance equation:

$$W = f\ (P_1,\ p,\ D,\ k,\ E,\ f_c,\ J) \tag{4.52a}$$

Traffic equation:

$$W = f\ (W_{AP},\ G_F,\ A_p,\ t) \tag{4.52b}$$

Swelling clay equation:

$$t = f\ (P_1,\ P_p,\ b,\ P) \tag{4.52c}$$

Most of the variables in these equations are known. Equations written in their simplest forms using only the unknown variables are

$$W = f\ (p) \tag{4.53a}$$

$$W = f\ (t) \tag{4.53b}$$

$$t = f\ (P) \tag{4.53c}$$

Several attempts were made to combine these equations and to solve them simultaneously for the value of t. The simplest method would have been to combine them mathematically so that they could be solved directly for the value of t. As the derivation of such a model is very complex, a decision was made to solve these equations by an iterative procedure resulting in a value of t acceptable within an allowable tolerance. The procedure when adapted on the computer showed acceptable efficiency.

According to the basic AASHO equation, the rate of change of serviceability index increases with the number of load applications (or time). Physically it means that pavement deterioration at any time is a function of present serviceability index of the pavement at that time. Expressing this mathematically

$$\frac{\partial p}{\partial W} = f\ (\text{loss of serviceability caused by traffic})$$

A generalized form of this observation is applied to the cases where swelling clays are also active. It is assumed that the rate of deterioration caused by traffic is a function of present serviceability produced as a result of both previous traffic and the swelling clay.

$$\frac{\partial}{\partial W} = f \text{ (loss of serviceability caused by traffic plus swelling clay)}$$

This approach is used in the RPS1 solution process by using small increments of serviceability index. A brief description of the method is discussed below in reference to Fig 10 which explains graphically the solution process.

A small decrement dP in P is substituted in the swelling clay equation and the corresponding increment in t is calculated as Δt . For very small values of swelling clay parameter this process is reversed. A small increment Δt in t is substituted in the swelling clay equation and the corresponding decrement in P is calculated as dP.

Increment Δt is substituted in the traffic equation to give an increment ΔW in the traffic. The value of dP when subtracted from the value of the initial serviceability index P_1 gives a new value P_m , which when used in the performance equation along with ΔW gives a value of p . The value $(P_m - p)$ is the serviceability loss due to the incremental traffic ΔW . The process is repeated until p approaches the value of terminal serviceability P_2 within a specified tolerance. The final value of t gives the desired life.

It is obvious from Fig 10 that serviceability loss due to swelling clay is considered continuous whereas the loss due to traffic is calculated in discrete steps along the performance curve. For each step, serviceability loss due to traffic is dependent upon the serviceability index at the beginning of the step. Contrary to this, the loss in serviceability due to swelling clay is independent and continuous. Physically it will mean that serviceability loss due to traffic is dependent upon swelling clay deterioration, but the loss in serviceability due to swelling clay is continuous and is not affected by load repetitions. The finer the value of decrement dP , the better the answers will be. An exact solution will be obtained when dP tends to zero.

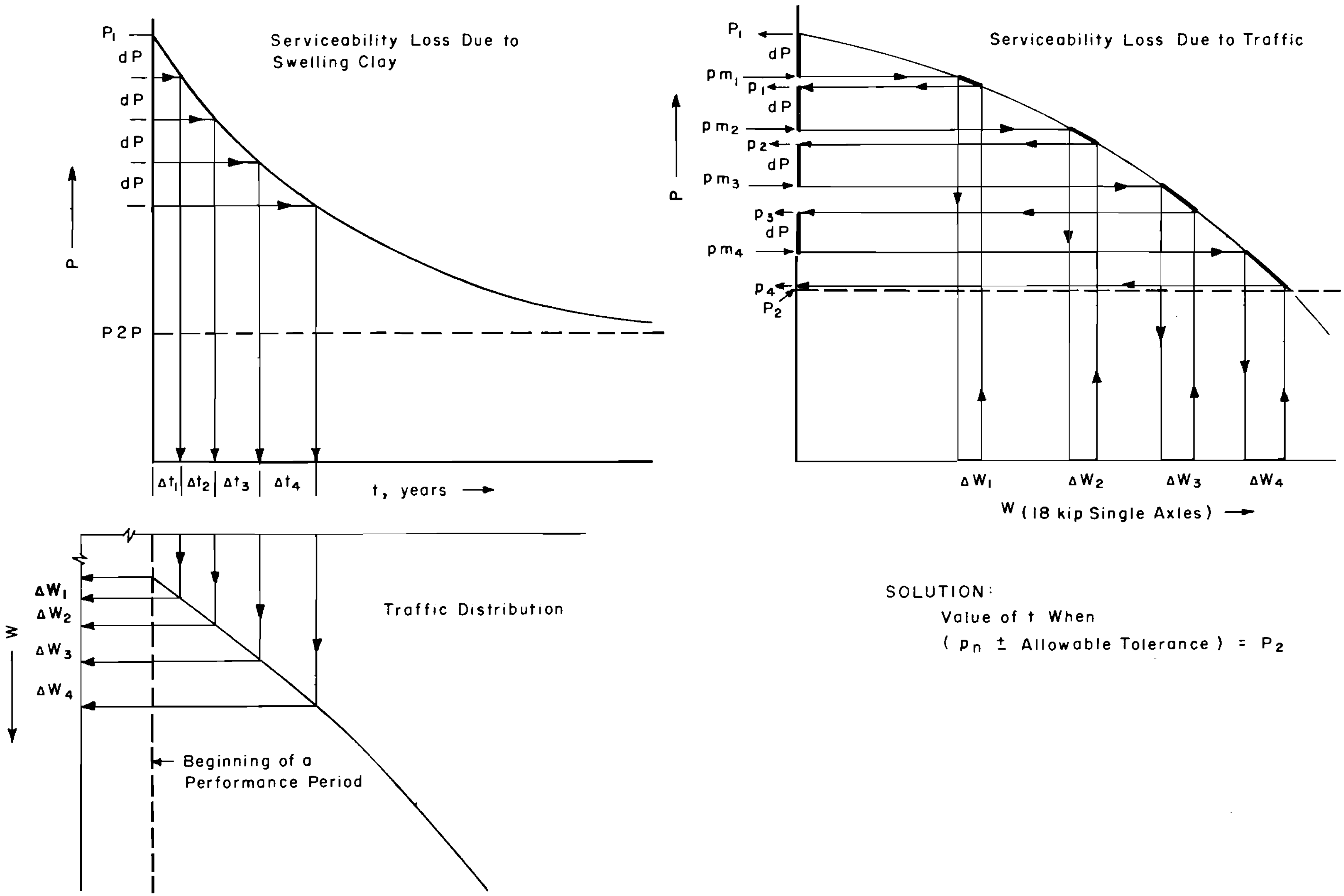


Fig 10. Illustrative process for simultaneous solution of performance, traffic, and swelling clay equations.

Models for Correlation of Material Properties

Certain relationships correlating material properties are used in RPS1 and are described below.

An empirical relationship is developed correlating the experimental data (Refs 61 and 77) available for Texas Triaxial Class T_{TC} of a material and its resilient modulus value M_R.

The relationship is

$$\log_{10} M_R = 4.906 - 0.107 \, T_{TC}^{1.5} \tag{4.54}$$

Since elastic layered theory is used to develop the model for improved modulus of support, the same loading is used to generate data to determine k values corresponding to various M_R values. The relation developed is

$$M_R = 23.925k \tag{4.55}$$

where

k = modulus of subgrade reaction.

CHAPTER 5. THE WORKING SYSTEMS MODEL

The rigid pavement system generates alternate solutions for the design with the help of a working systems model in the form of a computer program. The explicit mathematical models described in Chapter 4 are solved by this computer program. The computer program has been named Rigid Pavement System One, RPS1. A number has been added to the system ID to signify the stage of improvement. The number 1 designates this as the first working system for the design of rigid pavements. Subsequently, improved versions will be called RPS2, RPS3, and so on.

SYSTEM INPUTS

The design involves the use of a large number of input variables producing a large variety of pavement design options in a systematic manner. The exact number of pieces of information to be input depends upon the individual problem and can be determined from Table 1.

This relatively large set of inputs is subdivided into the following groupings:

(1) system controls;
(2) system constraints;
(3) performance variables;
(4) traffic volume, growth, and distribution variables;
(5) traffic delay variables;
(6) material properties;
(7) stochastic parameters;
(8) cost variables;
(9) environmental factors;
(10) dimensional inputs; and
(11) miscellaneous parameters.

A brief discussion of these groupings, the variables in each group, and their functions are described below.

TABLE 1. NUMBER OF INPUTS FOR PROGRAM RPS1

	Type of Input	Number of Inputs
(1)	Program controls	5
(2)	Traffic volume	1 + NL x 4
(3)	Traffic growth and distribution	5
(4)	Designer's restraints	9
(5)	Performance variables	5
(6)	Traffic delay variables	16
(7)	Concrete	1 + NC x 11
(8)	Concrete dimensions	3
(9)	Subgrade	6
(10)	Subbase	1 + NSB x 9
(11)	Bar streel longitudinal	NLB x 3
(12)	Bar steel transverse	NTB x 3
(13)	Wire mesh	NWM x 3
(14)	Tie bar steel	NTB x 3
(15)	Steel sizes	NB + 2 x NW + NT
(16)	Overlays	6
(17)	Seal coats	3
(18)	Joints	5
(19)	Maintenance, dimensions, and miscellaneous	8

Definitions

NL - number of load groups,
NC - number of concretes,
NSB - number of subbases,
NLB - number of longitudinal bar steels,
NTB - number of transverse bar steels,
NWM - number of wire mesh steels,
NTB - number of tie bar steels,
NB - number of deformed bar numbers,
NW - number of wire mesh sizes,
NT - number of tie bar numbers.

The program uses 114 different types of numerical inputs.

System Controls

The operation of the computer program is controlled by these optional parameters. To create maximum flexibility in design, three main options, giving rise to eight different types of designs, are built into the computer program. The options are for

(1) pavement type: jointed concrete pavements or continuously reinforced concrete pavements;

(2) overlay type: asphalt concrete overlays or portland cement concrete overlays; and

(3) reinforcement type: wire mesh reinforcement or deformed bar reinforcement.

Table 2 describes these different types of designs.

The user can specify both types of pavements and/or overlays and/or reinforcements to be analyzed.

The output for RPS1 can be varied also. The following options are available:

(1) the number of alternate strategies desired and

(2) the long or the short form of output.

Designs are printed in a summary table where the optimal design appears first, and the others are presented in the order of increasing total overall cost.

The long and the short forms of the output determine respectively whether or not to print out reinforcement size and layout and the seal coat schedule for each strategy printed in the summary table.

It may be noted that program controls largely determine the operation and output of the system, and thus, with their proper use, computation time can be largely decreased.

System Constraints

As the name implies, this set of variables enforces different restraints on the working system. A set of specified constraints generates the overall number of possible designs, which are then analyzed and checked against a number of other constraints located at various places in the system. The designs are rejected or accepted at these checks. A strategy which fulfills all the requirements of these restraints is a feasible strategy and is considered for the optimization process.

TABLE 2. TYPES OF DESIGN STRATEGIES WHICH CAN BE ANALYZED BY RPS1

Design type	1	2	3	4	5	6	7	8
Pavement type	JCP	JCP	JCP	JCP	CRCP	CRCP	CRCP	CRCP
Overlay type	AC	AC	PCC	PCC	AC	AC	PCC	PCC
Reinforcement type	WM	DB	WM	DB	WM	DB	WM	DB

JCP - jointed concrete pavements,

CRCP - continuously reinforced concrete pavements,

AC - asphalt concrete,

PCC - portland cement concrete

WM - wire meshes,

DB - deformed bars.

System constraints are different from the system controls in the sense that the latter control the types of solutions to be generated whereas the former formulate or reject the individual designs within those types.

Generally system constraints are the designer's decisions to generate a reasonable number of solutions, but at certain times they can be the actual physical limitations advocated by the special conditions of design and construction. The constraints decide the number of feasible designs considered for a particular problem and therefore may at times be very restrictive and reject some designs which are otherwise more economical. On the other hand, opening these restrictions beyond certain values may result in bringing a number of unnecessary designs under consideration and thereby increasing the computation time. For certain cases these constraints may increase the computation time considerably, and the solution process may itself become uneconomical. Therefore an efficient use of these variables should be made. These constraints are of two major types.

Constraints which limit the number of designs to be generated are

(1) minimum allowable concrete thickness;

(2) maximum allowable concrete thickness;

(3) increment at which concrete can practically be poured or the increment at which the solutions should be tried, whichever is greater;

(4) minimum allowable compacted thickness of each subbase;

(5) maximum allowable compacted thickness of each subbase;

(6) practical increment at which the subbase can be constructed or at which the solutions should be tried, whichever is greater, for each subbase;

(7) minimum asphalt concrete and/or portland cement concrete overlay thickness at one time;

(8) maximum total asphalt concrete and/or portland cement concrete overlay thickness; and

(9) wire mesh and/or deformed bar sizes to be tried for reinforcement.

Constraints which reject the generated designs or which partially abandon the process of generating designs of a certain kind are

(1) maximum funds available for initial construction,

(2) maximum total allowable thickness of initial construction,

(3) minimum time allowed for the first overlay,

(4) minimum time allowed between two consecutive overlays, and

(5) length of the analysis period.

Performance Variables

These variables are used in the system performance models to determine the life of an initial design or the overlayed structure when its serviceability index is allowed to drop from its initial value to a certain level specified as the minimum allowable for the facility under consideration. The performance model was developed by the statistical analysis of the serviceability trend values observed on the AASHO Road Test sections and therefore is supposed to be defined on the basis of the same distress responses as used at the Road Test or any other correlation thereof.

The following performance variables are used in RPS1:

(1) anticipated initial serviceability index of new pavement,

(2) minimum serviceability index to be maintained at all times for the facility,

(3) serviceability index which can be obtained after an overlay construction, and

(4) a theoretically assumed minimum value of the serviceability index which a pavement with no traffic will attain over an infinite period of time due to the effects of the swelling type of foundation soils.

Traffic Volume, Growth, and Distribution Variables

These inputs are used to specify the loads the pavement will have to carry during its analysis period. They are divided in two main groups:

(1) initial traffic volume and

(2) traffic growth and distribution.

Initial Traffic Volume. This includes

(1) number of axle load ranges which will sufficiently divide the axle weights into a reasonable number of groups,

(2) lower and upper value of each load range,

(3) type of axle,

(4) frequency of axles per day in both directions, and

(5) initial expected average daily traffic in one direction.

Traffic Growth and Distribution. These data determine the distribution of the above given traffic volume data over space and the projection in time during the analysis period. These growth and distribution variables of traffic are generally very complex and difficult to define and evaluate in a simple way. This design system contains simple versions of these growth factors which can easily be defined and quantified with the present state of available data and knowledge. These variables are

(1) percent per year of linear growth of the number of axles in each load range,

(2) percent per year of linear growth of the average daily traffic,

(3) percent of directional distribution of traffic, and

(4) percent of one-directional distribution of traffic for the design lane.

Traffic Delay Inputs

This set of variables is used to analyze the indirect economic costs of overlay construction incurred due to the inconvenience to traffic users. The present design system considers such inconvenience by mathematically calculating the costs of traffic delays and operating time losses.

Variables used to determine traffic delay costs are given in the following subgroups.

Speed Profile Variables. These variables indicate the anticipated changes in the speeds of vehicles at the time of overlay construction. They are

(1) approach speed of the vehicles from both directions to the overlay area,

(2) average through-speed of the traffic in the overlay direction, and

(3) average through-speed of the traffic in the nonoverlay direction.

Time Related Variables. These variables describe the time losses during traffic delay. They are

(1) average delay per vehicle moving in the overlay direction when it is stopped in the restricted zone by the construction equipment and/or personnel and

(2) average delay per vehicle moving in the nonoverlay direction when it is stopped in the restricted zone by the construction equipment and/or personnel.

Overlay Site Description Variables. These variables describe the overlay site and the distances over which the traffic will be affected. These variables are

(1) the model number describing the handling of traffic during the overlay operation,

(2) distance in the overlay direction over which the traffic is slowed,

(3) distance in the nonoverlay direction over which the traffic is slowed,

(4) distance of the alternate route if the traffic in the overlay direction is diverted,

(5) number of open lanes in the overlay direction in the restricted zone,

(6) number of open lanes in the nonoverlay direction in the restricted zone, and

(7) location of the facility, in a rural or urban area.

Traffic Variables. These describe the amount of original and affected traffic volumes during the overlay operation. They are

(1) percent of vehicles stopped by road equipment and personnel in the overlay direction,

(2) percent of vehicles stopped by road equipment and personnel in the nonoverlay direction, and

(3) percent of average daily traffic arriving during each hour of overlay construction.

Construction Time Variables. These variables determine the total number of hours that it will take to construct an overlay of a particular thickness. They are as follows:

(1) cubic feet per hour of asphalt concrete production,

(2) cubic feet per hour of cement concrete production, and

(3) number of hours per day that the overlay construction takes place.

Material Properties

These variables are required by various models of the system for analyzing the pavement structures. These are generally the engineering characteristics of the materials and can be determined in the laboratory or in the field with the exception of some which are theoretically defined. These properties are given below.

Subgrade. It is represented by the following properties:

(1) mean value of modulus of subgrade reaction or the mean Texas Triaxial Class of subgrade material,

(2) erodability factor for subgrade,

(3) swelling clay parameter, which is a mathematically described property of the subgrade representing the rate of loss of pavement serviceability of the system due to the swelling nature of the subgrade, and

(4) coefficient of friction between the subgrade and the concrete slab.

Subbase. Subbase is the layer of material which is used above the subgrade to improve its load supporting capacity. In the present procedure the improvement achieved by using a particular subbase is considered by computing the increased value of modulus of support reaction. The following properties of each of the subbase materials are input:

(1) resilient modulus or Texas Triaxial Class of subbase material,

(2) erodability factor for the subbase, and

(3) coefficient of friction between the subbase and the concrete slab.

The coefficient of friction is used to determine the temperature stresses produced in concrete due to the shrinkage or expansion of the concrete slab.

Concrete. In addition to the supporting strength of the foundation below the slab, the properties of the concrete are vital factors for the performance of a design. They are used in the performance models of the system to determine the life of a design as well as the amount of steel to be used in the design. The parameters to be input in the present system are

(1) mean value of the flexural strength of concrete, the position of the testing loads, and the age of the concrete samples when tested in days;

(2) modulus of elasticity of concrete at 28 days;

(3) weight of concrete; and

(4) tensile strength of concrete.

Reinforcement. This is generally used in concrete slabs to minimize temperature cracking. The steel property used for this purpose is the tensile yield point strength of steel.

Overlays. Overlays are provided on designs where the original slab does not last the required analysis period. Various models and techniques are built into this working system for the design and analysis of the composite structures resulting from the overlay thicknesses of different materials. For rigid overlays the same properties of concrete are used for overlays as for the concrete used in the initial design. In addition, the program requires the input of a theoretical concrete coefficient determining the load-carrying capacity of the existing slab as compared to a new slab. For asphalt concrete overlays the modulus of elasticity of asphalt concrete is the required input for the design.

Stochastic Parameters

For the nonhomogeneous materials used in pavements, the material properties change from point to point and are functions of time and environment. To take such variations into account, the dispersion data of the laboratory tests conducted to determine these properties can be utilized. Assuming the dispersion data for a material property to fall along a normal distribution curve, a design value can be found by specifying a certain level of confidence desired for design with respect to that particular material property. The present design system utilizes this concept for two important variables of design and requires the following inputs:

(1) standard deviation for the flexural strength of concrete,

(2) confidence level desired with respect to the flexural strength of concrete,

(3) standard deviation for the modulus of subgrade reaction or Texas Triaxial Class of subgrade, and

(4) confidence level desired with respect to the modulus of subgrade reaction or Texas Triaxial Class of subgrade.

Cost Inputs

The criterion of total overall cost is used for this working system to indicate the preference of any design over the other. The overall cost is calculated by considering the cost of materials, construction, maintenance, and other operations. A number of cost inputs are therefore required by the computer program for its evaluation of different strategies. These cost inputs are

(1) cost per lane-mile of subgrade preparation,

(2) initial cost per lane-mile of construction equipment for each subbase,

(3) in-place cost per compacted cubic yard of each subbase,

(4) initial cost per lane-mile of construction equipment for each type of concrete,

(5) unit cost per cubic yard for each concrete,

(6) cost per lane-mile of surfacing (curing and finishing) each concrete,

(7) cost per pound of each type of reinforcement,

(8) initial cost per lane-mile of construction equipment for asphalt concrete overlays,

(9) in-place cost per cubic yard of compacted asphalt concrete,

(10) present worth of any additional cost per square yard incurred for any special treatment of old pavement before an overlay construction,

(11) cost per lane-mile of providing a seal coat. The seal coats are used for pavement strategies provided with asphalt concrete overlays. The total cost of seal coats is determined with the help of the following schedule which is to be input:

   (a) minimum time to the first seal coat after an asphalt concrete overlay and

   (b) minimum time allowed between two consecutive seal coats,

(12) cost per foot of transverse joint,

(13) cost per foot of longitudinal joint,

(14) composite labor wage per unit of maintenance,

(15) composite equipment rental rate per unit of maintenance,

(16) cost of materials per unit of maintenance,

(17) salvage percent of structural value at the end of the analysis period, and

(18) percent interest rate or time value of money.

Environmental Factors

The only environmental effect built into the system at present is needed to compute the maintenance requirements of various designs and is an index of the number of days with freezing temperature per year.

Dimensional Inputs

These inputs determine the dimensions of the facility to be provided. They are

(1) number of total lanes to be provided in both directions,

(2) width of each lane,

(3) number of transverse construction or warping joints (if any) to be provided for continuously reinforced concrete pavements, and

(4) range of spacing (lower and upper values) specified for transverse joints in jointed concrete pavements.

Miscellaneous Parameters

Certain inputs do not fall in any of the above categories. They are provided to aid in other inputs and the computer output. They are

(1) number of concretes,

(2) number of subbases,

(3) description of subbases, and

(4) identifications for all reinforcements.

INPUT SUMMARY

For the sake of quick reference, all the inputs discussed earlier are presented in Table 3. The subdivisions of variables for this table are different from those described above and are the ones used in the computer program, for the sake of the convenience of data input. The names assigned to the variables in the computer program are also given.

GENERAL DESCRIPTION OF RPS1

The computer program RPS1 is written to solve various performance and cost models, giving arrays of designs and pertinent information. These strategies are stored and scanned for optimization by a technique utilizing minimum storage requirement and computational time. A general procedure of analysis is described in this section. A thorough understanding of the program can be achieved by going through, in addition to this section, various mathematical models used, the general flow diagram, and the listing of the computer program. Appendices 1 through 5, respectively, describe the operating manual, general flow diagram, listing of computer program, sample input, and the output for the example problem.

A summary flow chart for the program is shown in Fig 11. The program begins by reading all input data. A number of checks have been included for wrong data input and invalid parameters. A relevant error message is printed in such cases and the program is terminated. All data, if successfully read, are echo printed.

Based upon data input the design values of certain variables are found using probability. The subsequent design process can broadly be divided into the following major parts:

(1) generating possible initial designs,

(2) selecting feasible initial designs,

(3) developing overlay strategies,

(4) storing, optimization, and scanning, and

(5) output.

Each major part is discussed separately in the following sections.

TABLE 3. PROGRAM INPUTS, RPS1

(1) Program controls

(a) Control switch deciding the type or types of pavements to be designed, NCS1
(b) Control switch deciding the type or types of overlays to be designed, NCS2
(c) Control switch deciding the type or types of reinforcements to be designed, NCS3
(d) Control switch to decide whether to print the long or the short form of output, PSN1
(e) Control switch to specify the number of designs for the output in the summary table, PSN4.

(2) Traffic volume

(a) Number of axle load ranges, NL
(b) Lower value of load range, L1
(c) Upper value of load range, L2
(d) Type of axle, NCODE
(e) Number of axles per day in both directions for each load range, NA

(3) Traffic growth and distribution

(a) Axle growth factor, AGF
(b) ADT growth rate, ADTGR
(c) Directional distribution factor, DDF
(d) Lane distribution factor, DFL
(e) Initial one direction ADT expected, ADT

(4) Program restraints

(a) Maximum funds available for initial construction, CMAX
(b) Maximum total thickness of initial construction, TMAX
(c) Minimum time to the first overlay, OFMIN
(d) Minimum time between overlays, BOMIN
(e) Maximum accumulated thickness of all AC overlays, OMAXA
(f) Minimum thickness of a single AC overlay, OMINA
(g) Maximum accumulated thickness of all CC overlays, OMAXC
(h) Minimum thickness of a single CC overlay, OMINC
(i) Length of the analysis period, AP

(5) Performance variables

(a) Initial serviceability index, P1
(b) Terminal serviceability index, P2
(c) Serviceability index after an overlay, POV
(d) Minimum serviceability index which will be reached due to swelling clay alone, P2P
(e) Swelling clay exponent, BONE

(Continued)

TABLE 3. (Continued)

(6) Traffic delay variables

- (a) Distance over which traffic is allowed
  - (1) in overlay direction, DTSO
  - (2) in nonoverlay direction, DTSN
- (b) Detour distance of the alternate route, if adopted, DDOZ
- (c) Percent of ADT arriving during each hour of overlay construction, PAPH
- (d) Number of hours per day that the overlay construction takes place, HPDC
- (e) Number of open lanes in the restricted zone
  - (1) in overlay direction, NOLO
  - (2) in nonoverlay direction, NOLN
- (f) Project location, rural or urban, ITYPE
- (g) Percent of vehicles stopped by road equipment and personnel
  - (1) in overlay direction, PVSO
  - (2) in nonoverlay direction, PVSN
- (h) Average delay per vehicle stopped in the restricted zone
  - (1) in overlay direction, DEQO
  - (2) in nonoverlay direction, DEQN
- (i) Average approach speed of vehicles, AAS
- (j) Average speed through restricted zone
  - (1) in overlay direction, ASOD
  - (2) in nonoverlay direction, ASND
- (k) Model describing the traffic situation, MODEL

(7) Materials, concretes

- (a) Number of concrete types, NC
- (b) Number of days at which concrete strength was measured, ND
- (c) Position of loads for flexural strength test, center or third point, NP
- (d) Mean value of concrete flexural strength, SX
- (e) Concrete flexural strength standard deviation, SXSD
- (f) Confidence level desired with respect to concrete flexural strength, SXCL
- (g) Weight of concrete, WC
- (h) Modulus of elasticity of concrete, E
- (i) Tensile strength of concrete, TS
- (j) Initial cost of construction equipment, CIC
- (k) Unit cost per cubic yard of concrete, CPCYC
- (l) Cost of surfacing concrete, CSC

(8) Concrete dimensions

- (a) Minimum allowable concrete thickness, TCMIN
- (b) Maximum allowable concrete thickness, TCMAX
- (c) Practical increment at which concrete can be poured or the solutions to be tried, CINC

(9) Subgrade properties

- (a) Subgrade k, mean value, SGK
- (b) Subgrade k, standard deviation, SGKSD

(Continued)

TABLE 3. (Continued)

- (c) Subgrade k, confidence level, SGKCL
- (d) Texas Triaxial Class, mean value, TTC
- (e) Texas Triaxial Class, standard deviation, TTCSD
- (f) Texas Triaxial Class, confidence level, TTCCL
- (g) Friction factor for subgrade, FFSG
- (h) Erodability factor for subgrade, EFSG
- (i) Cost of subgrade preparation, CPLMSG

(10) Materials, subbases

- (a) Number of subbase types, NSB
- (b) Description of subbase, NAME
- (c) Erodability factor for the subbase, EF
- (d) Friction factor for subbase, FFSB
- (e) Texas Triaxial Class for subbase, TTCS
- (f) Subbase material modulus value, ES
- (g) Initial cost of construction equipment, CIS
- (h) Cost per cubic yard of compacted subbase, CPCYS
- (i) Minimum allowable subbase thickness, TSMIN
- (j) Maximum allowable subbase thickness, TSMAX
- (k) Practical increment at which subbase can be poured, SINC

(11) Materials, reinforcements

- (a) Longitudinal and transverse
  - (1) bar steel identification number, NAMEBS
  - (2) tensile yield point strength of bar steel, TYSBS
  - (3) cost per pound of bar steel, CPPBS
- (b) Wire mesh steel
  - (1) wire mesh steel identification number, NAMEWS
  - (2) tensile yield point strength of wire mesh steel, TYSWS
  - (3) cost per pound of wire mesh steel, CPPWS
- (c) Tie bar steel
  - (1) tie bar steel identification number, NAMETS
  - (2) tensile yield point strength of tie bar steel, TYSTS
  - (3) cost per pound of tie bar steel, CPPTS
- (d) Steel sizes
  - (1) bar numbers to be tried, BARN
  - (2) mesh spacings to be tried,
    - (a) longitudinal, SL
    - (b) transverse, ST
  - (3) tie bar numbers to be tried, TBARN

(12) Materials, overlays

- (a) Initial cost of construction equipment for AC overlays, CIOV
- (b) Cost per cubic yard of asphalt concrete, CPCYAC
- (c) Asphalt concrete modulus value, ACE
- (d) Asphalt concrete production rate, ACPR
- (e) Concrete production rate, CPR
- (f) Concrete coefficient, COEF
- (g) Any additional cost per square yard, present value, CPSYR

(Continued)

TABLE 3. (Continued)

(13) Seal coats

- (a) Time to first seal coat after an AC overlay, TFS
- (b) Time between seal coats, TBS
- (c) Cost per lane-mile of a seal coat, CPLMS

(14) Joints

- (a) Cost per foot of transverse joint, CPFTJ
- (b) Cost per foot of longitudinal joint, CPFLJ
- (c) Transverse joint spacing
  - (1) lower value, SLV
  - (2) upper value, SUV
- (d) Number of transverse joints, if any, provided for CRC pavements, NJM

(15) Maintenance, Dimensions, and Miscellaneous

- (a) Days of freezing temperature per year, DFTY
- (b) Composite labor wage for maintenance, CLW
- (c) Composite equipment rental rate for maintenance, CERR
- (d) Cost of materials for maintenance, CMAT
- (e) Interest rate or time value of money, RINT
- (f) Salvage percent of structural value at the end of analysis period, PSVGE
- (g) Width of each lane, WL
- (h) Total number of lanes in both directions, NLT

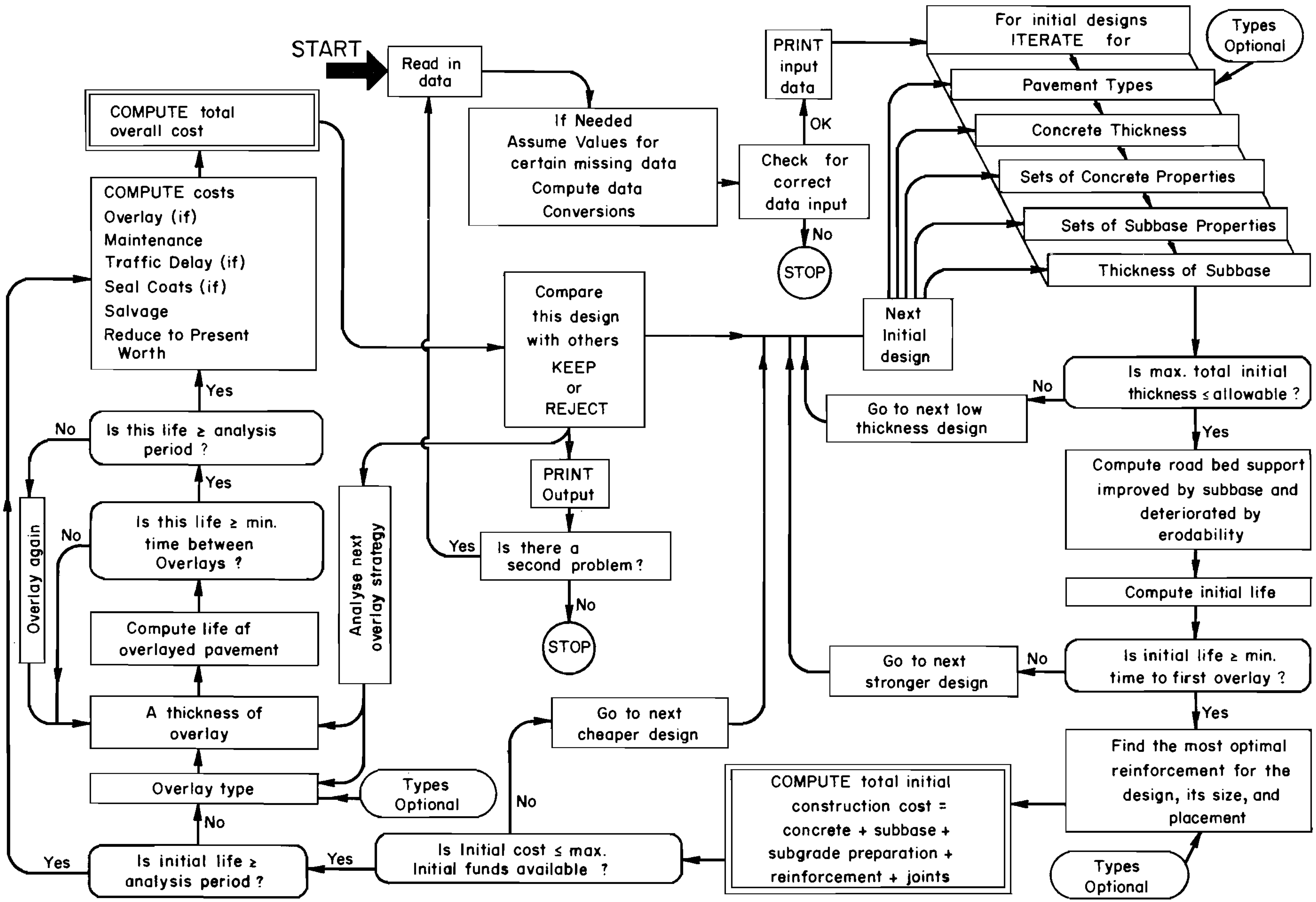


Fig 11. Summary Flow Diagram, RPS1.

Generating Possible Initial Designs

The thicknesses of concrete and subbases, starting with their minimum values and incrementing up to the maximum, produce a number of combinations of initial designs. These initial designs, when considered with different sets of concrete and subbase properties and for different types of pavements, produce a large number of initial designs, each of which is considered and analyzed separately. For efficiency in programming and to avoid unnecessary calculations, the initial designs are generated in RPS1 in the order shown in Fig 12.

Selecting Feasible Initial Designs

Each design of the possible initial design array discussed above is further analyzed as follows:

(1) equivalent traffic loads are computed for the design;

(2) improved roadbed support due to the subbase is calculated and then reduced for the specified erodability effect;

(3) initial life of the design is computed;

(4) reinforcement is designed and joint spacings are determined; and

(5) initial cost of the design is computed.

During this analysis, the initial design is subjected to three restraints specified by the designer:

(1) maximum allowable total thickness of initial construction,

(2) minimum time allowed for the first overlay after initial construction, and

(3) maximum allowable cost of initial construction.

If the design under consideration does not satisfy any of these three restraints, it is rejected. All the designs which do meet these restrictions are feasible initial designs.

The first restriction is active when the sum of the thicknesses of the concrete slab and the subbase is more than the maximum allowable total specified thickness. In terms of structural design, this restriction generally helps to avoid some of the designs having high subbase thicknesses.

The second restriction is applied when the first three of the above given steps of the analyses have been carried out. All the designs having their initial lives less than the allowable time before they can be overlayed are

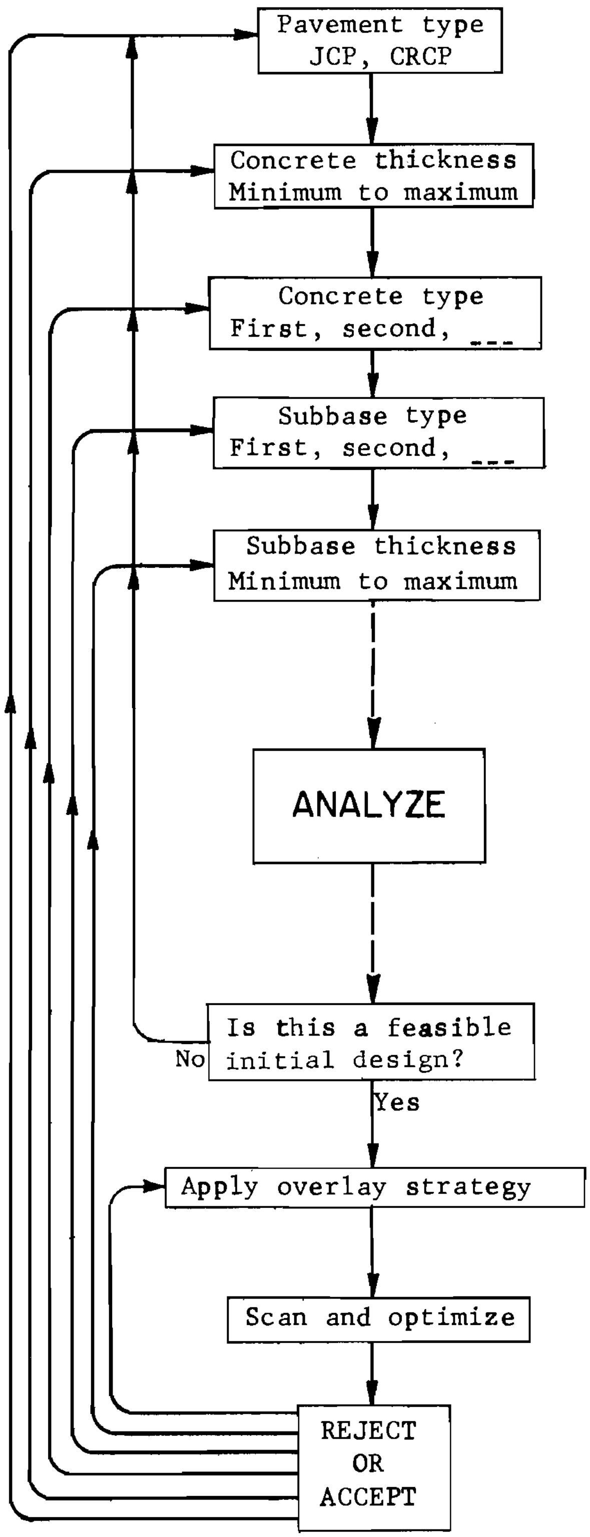


Fig 12. Process of generating designs in RPS1.

rejected as being unfeasible designs. Generally this restriction rejects initial designs which are relatively weak in their structural strength. For a designer following general current practices for providing overlays over initial construction, this restriction proves helpful in rejecting weak designs which require overlays in a short time after the initial construction.

Cost of initial construction is checked when all phases of an initial design contributing to cost are analyzed. The design is rejected if the cost of the design is more than the money available for initial construction. This is a very useful restriction for the designer who has a limited amount of money to start with and hopes to get more funds in the future.

The restrictions discussed above are very effective and useful from the analysis point of view but can be misleading if not properly used. For a particular set of design variables, certain values of these restrictions may reject initial designs which might otherwise have been found to be more economical, had the values of the restrictions been a little less restrictive. On the other hand, highly nonrestrictive values may in certain cases produce a large number of initial designs resulting in very high computation time. It is therefore recommended that values used for these restrictions be those which give a fair representation of all types of designs with respect to cost and strength.

The length of analysis period, though used as a parameter in several phases of the design process such as predicting traffic loads and being the ultimate criterion for a successful design, also acts theoretically as a restriction on initial designs. If an initial design with a particular concrete and subbase lasts the analysis period, all such designs which have the same concrete thickness and larger subbase thicknesses are rejected.

The designs which meet all the restrictions are called feasible initial designs and, except for the designs whose initial lives last the analysis period, are taken to the overlay subsystem for designing overlay strategies.

Developing Overlay Strategies

Every initial design which does not last the analysis period but meets all other feasibility requirements is overlayed with portland cement concrete or asphalt concrete overlays, as specified. Miminum thickness of the overlay and maximum combined thickness of all overlays is specified by the program user.

As soon as an initial design falls to its terminal serviceability index level, an overlay is provided and the composite structure is reanalyzed for its life.

Every overlay life is subjected to a restraint specified by the designer. If a strategy requires its next overlay before the minimum specified time between overlays, it is abandoned. Once an initial design is started to be overlayed, the program adopts the following procedure:

(1) The minimum thickness of an overlay is provided and again the life up to the minimum allowable serviceability index is calculated.

(2) If this life is less than the minimum time between overlays, the overlay thickness is incremented and the structure is reanalyzed.

(3) If the life of a composite structure does satisfy the time-between-overlay requirement but the total life including overlay life is still less than the analysis period, the structure is again overlayed with the minimum allowable thickness. This procedure is followed until any of the following happens:

   (a) Number of overlays exceeds eight.

   (b) The total thickness of all overlays provided exceeds the specified value. In this case, the procedure increases the thickness of the previous overlay and analysis is resumed.

   (c) The total life after an overlay is more than the analysis period. This is considered to be a successful strategy. The program, having met this condition, tries other overlay strategies which can be possible.

For a successful overlay, the cost of providing the overlay, the cost of traffic delay during the overlay operation, and the cost of maintenance over the life of the overlay are calculated. The total cost for each individual item is also computed and stored.

For the sake of illustrating the number of possible overlay strategies which may be analyzed for a design, the following simple example is given.

If an overlay with a minimum thickness value at one time of 2 inches and a total maximum overlay thickness of 9 inches is to be provided, and if the increment specified is one inch, there will be 21 different overlay strategies possible. Table 4 illustrates the patterns of these overlay thickness combinations.

In the actual solution process, all the strategies shown in this table may or may not be tried. For example, if strategy number 2 does survive the analysis period, number 3 will not be considered. Similarly, if the first two overlays of strategy number 1 survive the analysis period, the next one to be

TABLE 4. AN EXAMPLE FOR THICKNESSES OF VARIOUS POSSIBLE OVERLAY STRATEGIES

(Minimum overlay thickness at one time = 2.0 inches, maximum total overlay thickness = 8.0 inches, thickness increment = 1.0 inch.)

Strategy Number	Thickness of Overlay 1	Thickness of Overlay 2	Thickness of Overlay 3	Thickness of Overlay 4	Total Overlay Thickness
1	2.0	2.0	2.0	2.0	8.0
2	2.0	2.0	3.0		7.0
3	2.0	2.0	4.0		8.0
4	2.0	3.0	2.0		7.0
5	2.0	3.0	3.0		8.0
6	2.0	4.0	2.0		8.0
7	2.0	5.0			7.0
8	2.0	6.0			8.0
9	3.0	2.0	2.0		7.0
10	3.0	2.0	3.0		8.0
11	3.0	3.0	2.0		8.0
12	3.0	4.0			7.0
13	3.0	5.0			8.0
14	4.0	2.0	2.0		8.0
15	4.0	3.0			7.0
16	4.0	4.0			8.0
17	5.0	2.0			7.0
18	5.0	3.0			8.0
19	6.0	2.0			8.0
20	7.0				7.0
21	8.0				8.0

tried will be number 9, in anticipation that the increased thickness of the first overlay may last the analysis period. Designs number 2 through 8 will be rejected in that case.

Figure 13 graphically illustrates the general overlay performance patterns and also compares the relative differences in the performance patterns of initial designs with low, medium, and high structural strengths. This figure does not represent an actual problem.

Storing, Scanning, and Optimization

Storage of generated information can be a considerable problem in a program such as RPS1. The program is designed to consider an unlimited number of initial designs and overlay strategies. The big volume of pertinent information accompanying every strategy makes it necessary to store at one time as small a number of designs as possible.

Designs are optimized for total overall cost and a certain number of designs NREQ, as specified by the program input, are printed out. The optimization process, therefore, itself requires a design storage at least equal to the NREQ number of spaces. A method is devised to use this minimum storage at all times.

The computational process is arranged so that every strategy is designed and its pertinent information computed up to its overall cost. This overall cost is compared with the overall costs of all the strategies previously stored and the new design is either rejected or accepted according to decision criteria built into the program, as follows.

The program keeps every design until the first NREQ designs are stored. For every design after this, the total costs of the designs in storage are scanned and the index number of the design which has the maximum total cost is determined. If the total cost of the new design is less than this cost, the new design is accepted and it takes the place of the design with the highest total cost. Otherwise, the new design is rejected and the program analyzes the next design.

The output is printed, with the summary table having the information of the designs in the order of increasing total overall cost. As is indicated by the process explained above, a minimum of computer storage is utilized with the method adopted. The computer work for optimization is also kept to a minimum. The whole optimization process consists of scanning the total cost,

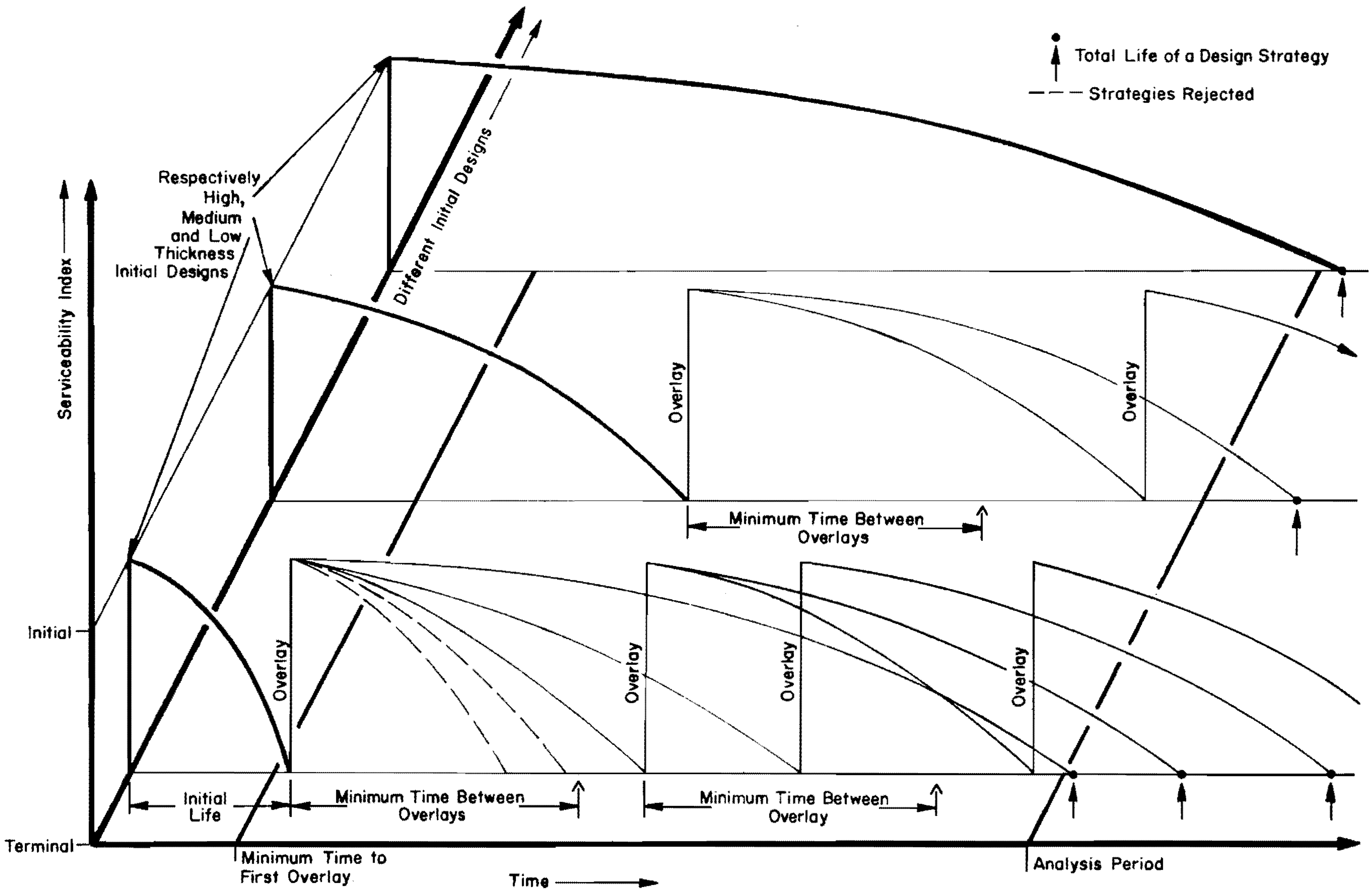


Fig 13. Illustrative performance patterns of overlays in RPS1.

finding the index numbers of designs, replacing a design if required, and finally determining the order of designs for output by their index numbers. The output part of the program gets a little involved with this kind of optimization process, but the relative disadvantage is insignificant. Figure 14 illustrates the process discussed above, in the form of an easily understandable flow chart.

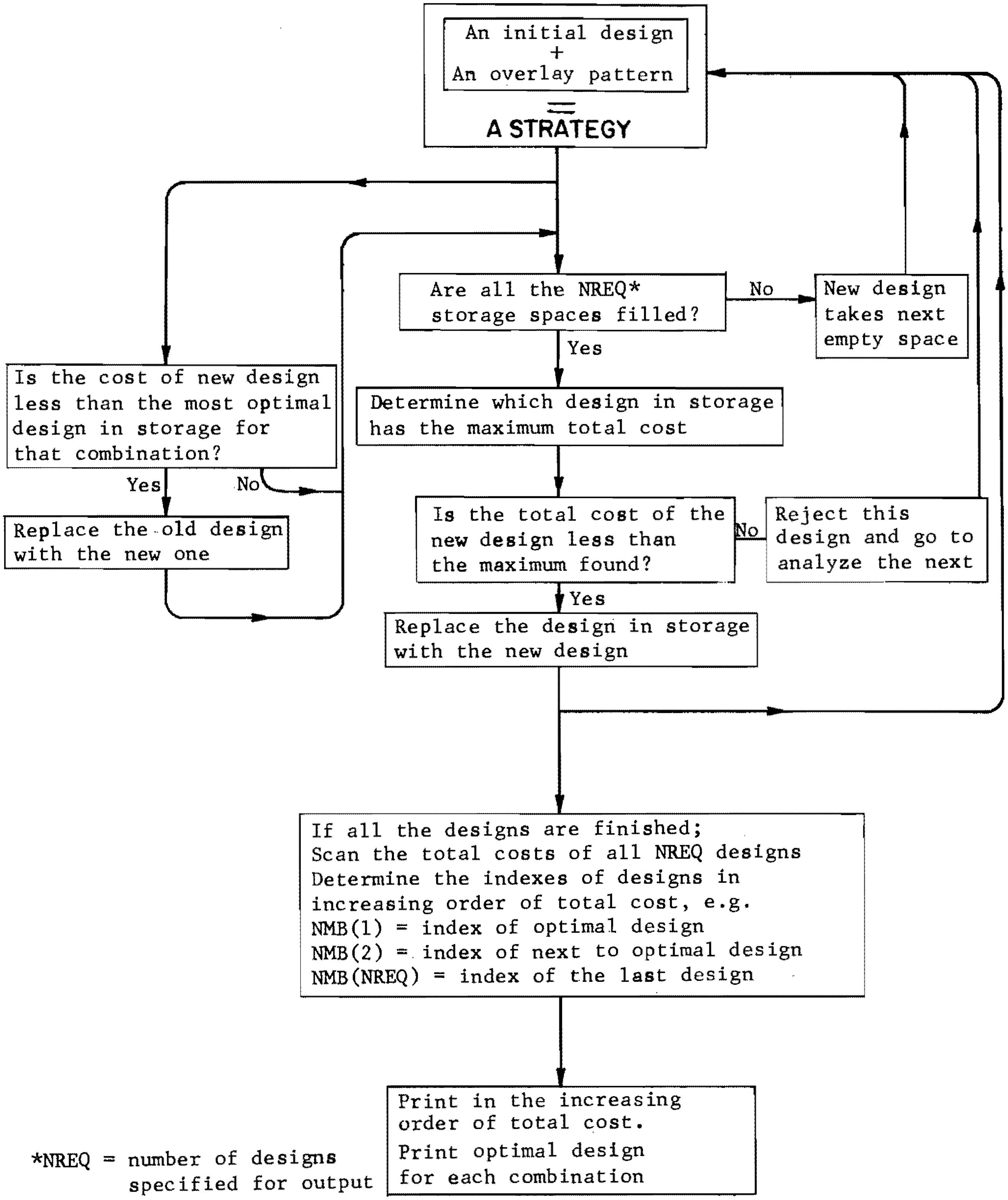
During the optimization process, the program also stores the optimal design for each combination of pavement-overlay type. Every new design belonging to a particular combination is tested against the design already in storage for that combination. The design is rejected or accepted according to whether its cost is more or less than the design in storage. There being a maximum of four different pavement-overlay combinations, four storage spaces, NREQ+1 to NREQ+4, are reserved to keep these optimal designs. If an initial design lasts the analysis period, further designs with increased thicknesses of the same concrete and subbase are not considered for analysis. The most optimal initial design which lasts the analysis period, if any, is stored in a separate array NREQ+5. Thus, in addition to NREQ storage arrays used for storing the specified number of designs for output, five more arrays are reserved for optimal designs out of various combinations.

Output

The design and cost information stored as discussed in the previous section is finally printed when all possible strategies are analyzed. Due to methods used for economizing storage and computation time, the program stores information in arrays which can be printed very easily with the use of subscripted subscripts. Because of the inability of the present FORTRAN compilers to handle such arrays, a new procedure is adopted for the output. The designs are handled in groups of six in increasing order of their total costs starting with the optimal design. Each group is shuffled in six spaces assigned for this purpose and then printed for output. The procedure requires very small additional storage, as it reuses five already reserved spaces for keeping the optimal designs, as discussed above.

DESCRIPTION OF RPS1 OUTPUT

All information necessary for the designer to investigate a variety of pavement strategies is printed at the end of the problem analysis. Three kinds of output are printed.



*NREQ = number of designs specified for output

Fig 14. Optimization procedure RPS1.

Optimal Designs for the Combinations

There are four types of pavement-overlay combinations which can be analyzed by the program:

(1) jointed concrete pavements with asphalt concrete overlays,

(2) jointed concrete pavements with portland cement concrete overlays,

(3) continuously reinforced concrete pavements with asphalt concrete overlays, and

(4) continuously reinforced concrete pavements with portland cement concrete overlays.

The optimal designs for the combinations specified by the designer are printed in RPS1 output. In addition, the optimal initial design which lasts the analysis period without any overlays, if there is one, is also printed.

Summary Table

A summary table describing as many nearly optimal strategies as specified by the designer is also printed. These strategies are printed in the increasing order of total overall cost. The optimization for summary table includes all the designs of every combination tried, including the one without overlays. The first design of the summary table is therefore the most economical design possible for the given input.

Design Analysis

The last page of the output contains a summary of the number of possible strategies, the rejected number of strategies due to each restraint specified by the designer, and the total strategies possible for the problem. All important information is given in two parts.

Initial Design Analysis. This describes the following:

(1) the total initial designs possible for the problem,

(2) number of designs rejected because their initial thicknesses are greater than the allowable value,

(3) number of designs rejected because their initial lives are less than the allowable minimum time to the first overlay,

(4) number of designs rejected because their costs are more than the money available for initial construction,

(5) number of acceptable initial designs lasting the analysis period,

(6) number of unacceptable initial designs lasting the analysis period, and

(7) number of initial designs for which overlay strategies are formulated.

Overlay Subsystem Analysis. This describes the following for each combination analyzed by the program:

(1) total number of acceptable strategies designed,

(2) number of strategies rejected during analysis because of maximum overlay thickness restraint,

(3) number of strategies rejected during analysis because the lives of the overlays provided are less than the minimum specified time between overlays.

(4) number of strategies rejected because the number of overlays required is more than eight, and

(5) number of times when each subroutine is called.

Contrary to the initial design analysis which accounts for every possible initial design, overlay subsystem analysis is only indicative of the relative constraining effects of various constraints provided. The process of disconcontinuing the analysis of a strategy on meeting a restraint, the selection of the next strategy for analysis in such cases, and the automatic rejection of several strategies due to criteria built into RPS1 is a complicated process. The designer should understand the computer program and the general flow diagram for completely understanding this part of the output.

Output Information for a Design

The following information is provided for each design listed in the output of the program.

(1) the type of pavement, overlay, and reinforcement;

(2) identification of concrete, subbase, and reinforcement used;

(3) thickness of concrete and subbase used for initial construction;

(4) reinforcement size and spacing;

(5) subsequent overlay thicknesses to be provided;

(6) initial life, life after each overlay, and the total life of the strategy;

(7) various initial construction costs;

(8) various costs of subsequent construction and maintenance; and

(9) overall cost of the design.

Total overall cost of a design, in addition to initial cost, consists of

(1) overlay construction cost,
(2) traffic delay cost during overlay construction,
(3) maintenance cost,
(4) seal coat cost, if provided; and
(5) salvage returns.

It may be emphasized that all costs incurred in the future are discounted to their present values by the interest rate specified by the designer. Overlay and traffic delay cost is the sum of all such costs discounted separately from the time they are incurred. Maintenance cost is calculated only for the analysis period even if the design life exceeds the analysis period. The cost shown for the maintenance is the sum of each year's separately discounted maintenance cost. Similarly, for the seal coats, if provided, the costs are discounted to the present value from the time they are provided. Salvage returns are discounted from the end of the analysis period.

EXAMPLE PROBLEM

An example problem has been solved and its output is given in Appendix 5. The output consists of the echo printing of the input data as well as the solution of the problem. The example problem is described as follows.

A facility on the interstate system is designed for a rural area to carry high-speed high-volume traffic. The facility will carry an initial average daily traffic of 10,000 vehicles with a 5 percent per year growth. The traffic loads are such that about 5 million equivalent 18-kip single axles will be obtained during a lifetime of 20 years. Serviceability index values after the initial construction and after an overlay construction are estimated to be, respectively, 4.2 and 4.0. A minimum serviceability index of 2.5 will be maintained at all times.

Initial funds of $6.25 per square yard of pavement are available. It is specified that pavement will not be overlayed during the first five years after the initial construction or in the first six years after an overlay construction. Initial total thickness of construction is not restricted.

The facility passes through an area of moderate swelling clays. The subgrade has a mean value of modulus of subgrade reaction of 100 pci with a standard deviation of 15 pci. Two subbases, one granular and one cement-treated, are available with modulus values of 20,000 and 900,000 psi, respectively. Granular subbases are observed to create a mild loss of support during their service life, whereas cement-treated subbases remain very stable. A low and a high strength concrete are available with mean flexural strengths of 450 and 650 psi and standard deviations of 40 and 60 psi, respectively. It is specified that the design should have a confidence level of 95 percent with respect to both subgrade modulus and concrete flexural strength.

The solution for the above problem generated 196 initial possible designs out of which 117 designs were rejected due to the different restraints specified above. The remaining 79 initial designs gave rise to 751 strategies, out of which 657 were feasible.

Twelve nearly optimal designs are printed in the output. These consist of jointed and continuously reinforced pavements with wire mesh or deformed bar reinforcements to be provided in initial construction and asphalt concrete overlays to be provided in the future. Present worth of the total cost for these designs varies from \$5.432 per square yard (for the optimal design) to \$5.606 per square yard (for the 12th nearly optimal design).

CHAPTER 6. SENSITIVITY ANALYSIS OF THE WORKING SYSTEMS MODEL

Program RPS1 is the first version of a systematic design procedure for rigid pavements. It links a large number of mathematical models quantifying various aspects of design into a working systems model. A large number of variables known to influence pavement performance are considered in the procedure.

The validity of such a system can only be ascertained through actual implementation and the feedback. Implementation requires enough initial confidence in the system and its concepts with respect to design and economy to stimulate the process of its adoption. Such confidence can be gained by a sensitivity analysis of the system, studying the behavior of different models and the relative effects and interactions of individual variables.

The complete study of this nature, being very elaborate and complex, will be a topic of future research. However, a small experiment for sensitivity analysis was undertaken at this stage with the following objectives:

(1) to gain confidence in the use of the computer program;

(2) to establish the "reasonableness" of the solutions;

(3) to check the functioning of various models and concepts used;

(4) to debug the program, find anomalies and problem areas, and determine approximate estimates of computation time required; and

(5) to have a feel for the cost sensitivity of some important variables of the system.

With these objectives in view a small experiment was undertaken. Based upon engineering judgment, all the variables of the system are given certain values called their "average" values and a solution is obtained for this average problem. The output for this average problem is given in Appendix 5.

STUDY OF IMPORTANT DESIGN VARIABLES

By the experience gained during the development of the program and other studies (Refs 67 and 132), ten important variables are selected and each variable is assigned a low and a high value. Two problems are solved for every variable, one with each of the low and the high value, while the values of all other variables are held at their average levels. Table 5 describes the variables chosen for study, the low and high values given to these variables and the design information obtained by solving the problems at these levels. Figure 15 describes the plots of optimal costs versus the values of the variables, both as percentages of the values for the average problem. The cost and design sensitivity of each variable are discussed as follows.

Total Equivalent 18-Kip Axles

Total applications of equivalent 18-kip axles determined by the traffic input are distributed over the entire analysis period according to the traffic equation (Eq 4.6). A higher traffic density, say in terms of applications per year, requires structurally stronger designs which cost more and thereby result in an optimal design having higher cost. As can be noticed by comparing optimal cost curves in Fig 15 this is one of the variables highly sensitive to cost.

One Direction Initial Average Daily Traffic

This variable is used for the calculation of traffic delay cost during the overlay construction and does not affect the structural strength requirements of the system. However, with a higher value of ADT the designs having higher serviceability lives and fewer overlays are preferred. The designer should be careful about the input for this variable and not make the facility saturated with traffic.

Traffic delay cost increases very rapidly beyond a certain value of ADT arriving during overlay construction. Such a trend can be noted in Fig 15. A traffic volume of about 1500 vehicles per hour in one lane during the overlay construction period will result in exceptionally high traffic delay cost (Ref 67).

Initial and Terminal Serviceability Indices

These limits on serviceability indices are imposed, depending on the type of facility to be designed. Performance as determined by traffic is always modified by the serviceability loss function due to the swelling clay. Since the combined effect is complex, observations on the effects of initial and terminal serviceability indices are very involved. However, it has been noted that the difference in initial and terminal serviceability, called "range of serviceability loss," is an important factor from the design and cost point of

TABLE 5. SENSITIVITY ANALYSIS OF VARIABLES

	Value	Value, percent of average	Most optimal cost, dollars per sq. yd.	Most optimal cost, percent of average	Feasible initial designs	Total feasible strategies
Average Problem		100%	5.432	100%	79	657
Total 18 kip axles, two directions						
Low	$.5\times10^6$	10%	4.528	83.3	126	329
Average	5×10^6					
High	10×10^6	200%	5.800	106.7	49	618
Average daily traffic, one direction						
Low	1,000	10%	5.362	98.7	79	657
Average	10,000					
High	15,000	150%	5.800	106.7	79	657
Initial serviceability index						
Low	4.0	95%	5.448	100.2	71	544
Average	4.2					
High	4.5	107%	5.411	99.6	81	632
Terminal serviceability index						
Low	1.5	60%	5.103	93.9	192	427
Average	2.5					
High	3.0	120%	5.652	104.0	55	1058

(Continued)

TABLE 5. (Continued)

	Value	Value, percent of average	Most optimal cost, dollars per sq. yd.	Most optimal cost, percent of average	Feasible initial designs	Total feasible strategies
Average Problem		100%	5.432	100%	79	657
Swelling clay parameter						
Low	0.0	0%	5.115	94.1	81	370
Average	0.06					
High	0.15	250%	5.834	107.4	42	703
Concrete flexural strength, psi						
Low	360, 520	80%	6.003	110.5	39	617
Average	450, 650					
High	540, 780	120%	5.020	92.4	100	535
Subgrade k value, pci						
Low	40	40%	5.481	100.9	59	527
Average	100					
High	300	300%	4.855	89.3	95	534
Asphalt concrete modulus, psi						
Low	80,000	40%	5.437	100.1	79	702
Average	200,000					
High	1,000,000	500%	5.345	98.4	79	468

(Continued)

TABLE 5. (Continued)

	Value	Value, percent of average	Most optimal cost, dollars per sq. yd.	Most optimal cost, percent of average	Feasible initial designs	Total feasible strategies
Average Problem		100%	5.432	100%	79	657
Salvage percent						
Low	0.0%	0%	6.178	113.7	79	657
Average	50.0%					
High	100.0%	200%	4.543	83.6	79	657
Interest rate, percent						
Low	0.0%	0%	4.840	89.1	79	657
Average	5.0%					
High	10.0%	200%	5.412	99.6	79	657

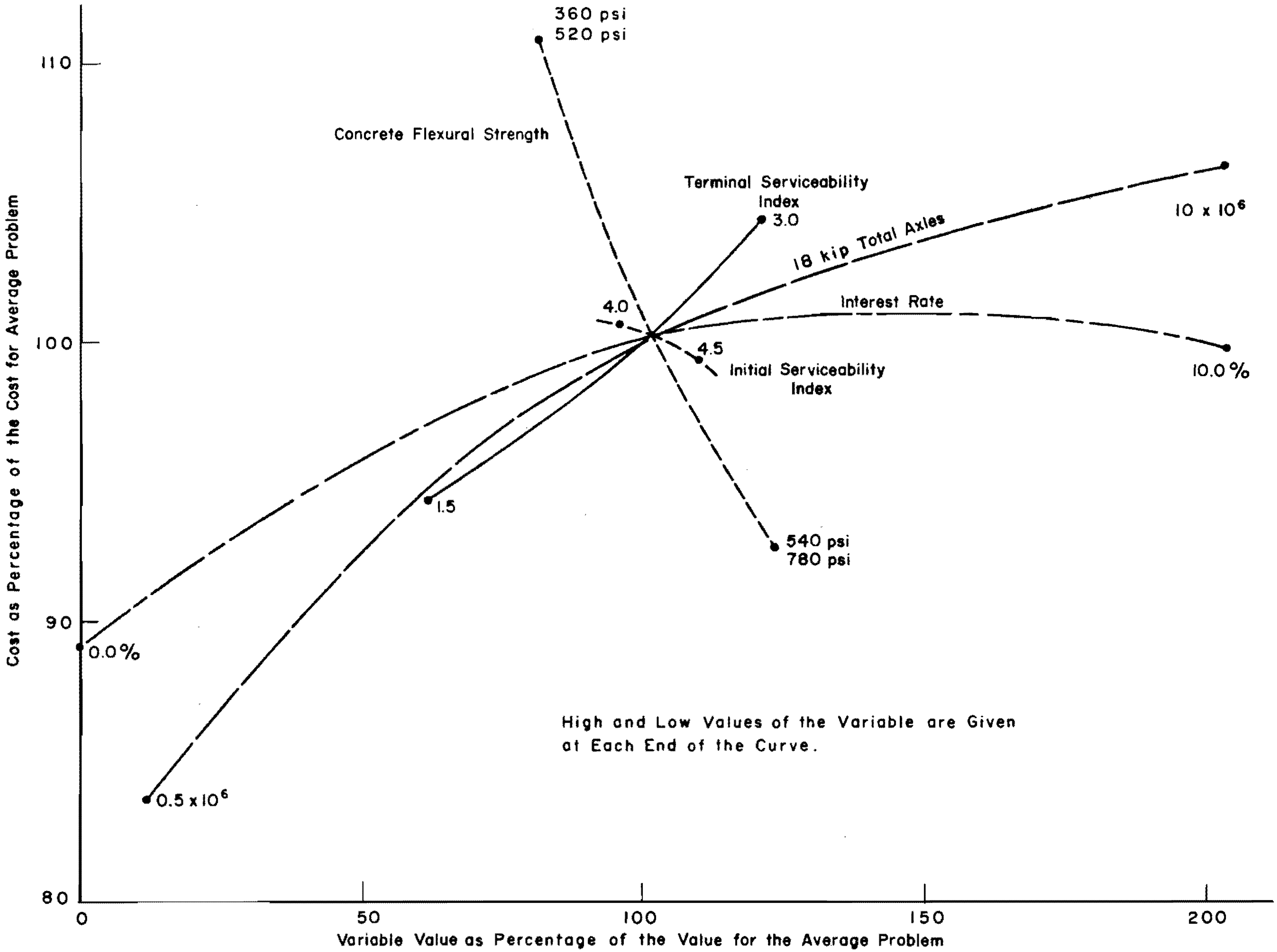


Fig 15. Sensitivity analysis curves.

(Continued)

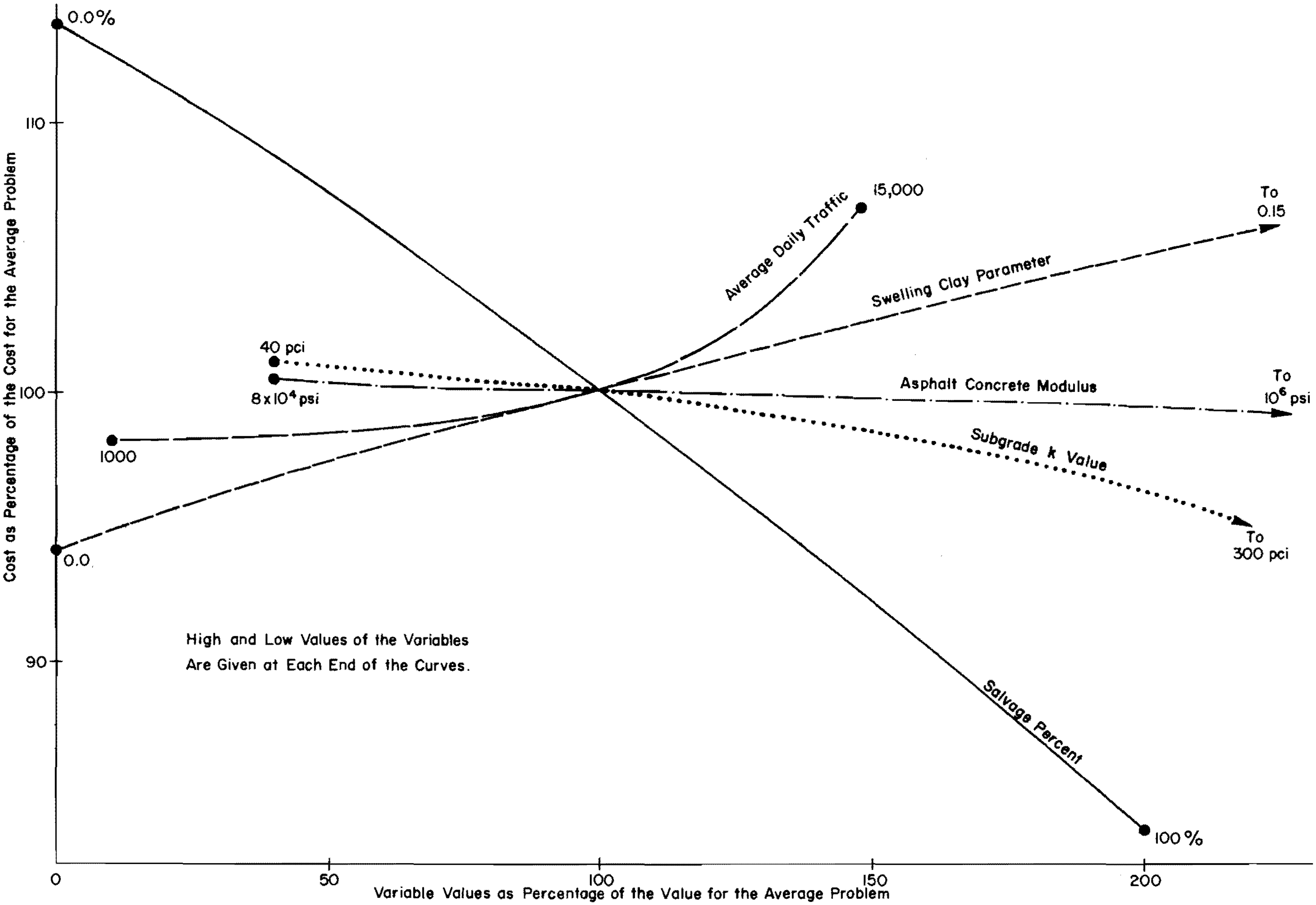


Fig 15. (Continued)

view. This range is the "serviceability loss potential" for a facility and a higher value of this range reduces the structural strength requirements by increasing the lives of the designs. The cost of the optimal design is therefore reduced.

To isolate the effects of the "range of serviceability loss" a set of problems with no swelling clay effects is solved. It has been observed that the higher a particular "range" is placed on the serviceability index scale, the longer the lives of the designs will be.

Swelling Clay Parameter

Initial studies conducted to incorporate this variable in the system revealed a very high sensitivity of the variable with respect to structural requirements of the system. The life of a design is shortened with a higher value of this parameter.

It has been found that a smaller value for minimum time to the first overlay should be used with a high value of this parameter. The smaller value of time will allow more such designs to be considered which have small initial thicknesses. Since serviceability loss due to swelling clay has the same rate irrespective of the thickness provided, weaker initial designs will be more economical in the long run.

Concrete Flexural Strength

The optimal cost curve for flexural strength has the maximum average slope per percent change in the variable. Similar observations are also made in another study (Ref 132) done in relation to the effects of flexural strength on the load applications given by the performance equation used in RPS1. This is the main reason that a confidence level has been included in RPS1 to take into account the statistical variations of this important variable under actual construction conditions.

Modulus of Subgrade Reaction

In the analysis this parameter is modified by the standard deviation and confidence level specified with respect to this parameter, the thickness, and the type of subbase used. The modified values used for analyzing the structural capacities of different designs therefore make a direct inference as to the effect of this variable very difficult. In general, the cost of the most optimal design reduces with an increase in the value of the modulus of subgrade reaction.

Asphalt Concrete Modulus Value

A higher value of this variable gives higher lives for the pavements with asphalt concrete overlays. The variable has a relatively small effect on cost.

Salvage Percent

This variable is defined as the returns in percent of the cost of initial and overlay materials at the time when a pavement is abandoned. As can be noted from optimal cost curves, salvage percent is one of the important variables. A change in this variable causes proportionate changes in the total costs of all feasible strategies. The changes in costs of all the strategies in turn affect the selection of near optimal designs for the output, their order, and their costs.

Interest Rate

The interest rate gives the present value of money spent in future overlays, maintenance, and seal coats. Likewise, it gives the present value of salvage returns. A change in interest rate varies all parts of total overall cost except that of initial construction.

In general, the further in future a cost is incurred, the smaller the present value will be. A rearrangement of the strategies is observed in the summary table with a change in this parameter. Generally the designs with smaller initial lives are shifted towards the optimal design when interest rate is increased.

STUDY OF SYSTEM CONSTRAINTS

In addition to the above analysis, effects of system restraints are studied by changing their values from those used in the average problem. Variations and the results are shown in Table 6.

In each case a more restrictive value of the parameter is used to demonstrate the effect on cost of improper use of these parameters. The number of feasible initial designs may decrease with more restrictive values of these parameters. The optimal cost is not affected until any of these parameters becomes a restriction over the solution. Therefore, the designer should be careful in

TABLE 6. A STUDY OF RESTRAINTS

Restraint	Value for average solution	Value studied	Most optimal cost dollar per sq. yd.	Initial designs (out of possible 196) rejected due to the restraint of: Total initial thickness not satisfied	Initial life not satisfied	Initial funds not available	Feasible initial designs	Total feasible strategies
Average Problem			5.432	0	56	61	79	657
Time to first overlay	5.00	7.50	5.510	0	86	61	49	190
Time between overlays	6.00	9.00	5.609	0	56	61	79	440
Length of analysis period	20.00	25.00	5.782	0	56	61	79	1289
Maximum total initial thickness	24.00	12.00*	5.552	188	5	0	3	32
Maximum initial funds available	6.25	4.50*	5.552	0	28	160	8	80

* For obtaining reasonable solution, time to the first overlay was taken = 2.5 years along with this variation.

selecting values so that, if selected to decrease the computation time, they do not reach levels where the optimal design is rejected.

Minimum allowable times to the first overlay and between overlays give the designer a varied choice to obtain different patterns of stage construction. As these values are increased, the thickness requirements of initial designs and overlays also increase.

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Sensitivity study shows that the system developed meets the limited test of reasonableness of solutions and procedure logic. The designs and their costs are realistic.

It may be noted that the cost and the design sensitivities of the system with respect to the changes in different variables and restraints, as discussed in this chapter, are only relative. Slope of a curve in Fig 15 will change with the level of the average value used for the variable as well as for other variables of the system. However, the qualitative trends will remain the same.

CHAPTER 7. SUMMARY AND FUTURE RESEARCH

This report presents a rigid pavement design procedure as a part of an overall pavement management system based on broad principles of systems engineering. Existing state-of-the-art models modified and improved by additional mathematical work have been combined in a rational and meaningful way, based upon economic concepts. A sound basic structure has been given to the computer program in an easy and generalized framework so that future modifications can be incorporated in it with a minimum of effort.

As additional knowledge is obtained through further research, the precision and validity of the assumptions and extrapolations will be questioned from time to time, and thus the present working systems model is provisional in nature.

Within the available time, great effort has been made to evolve an efficient computer program and design procedure. Certain additional improvements in the program, with a small amount of additional effort, will be of great value to the user. The improvements are suggested as follows:

(1) The program logic of subroutine LIFE which consumes a major portion of computer time should be improved.

(2) Subroutine TDC to calculate traffic delay cost can be improved to obtain additional accuracy in the results.

(3) Deteriorated condition of the pavement should be adequately considered at the time of overlay construction. Fatigue principles can be used for this purpose.

(4) The model for the design of portland cement concrete overlays is inadequate and should be improved.

(5) Stochastic concepts can be extended for other parameters as well as for overall design.

(6) The maintenance model used at present is mainly developed for interstate highways. It should be modified to take into account other types of roads. An option can be provided for using the maintenance cost as a direct input. Also, maintenance schedules for the strategies should be printed out for the designer's future use.

(7) The model for the value of the swelling clay parameter BONE, used after an overlay construction, needs to be revised as it gives apparently undesirable results for certain ranges.

(8) The strategies as designed by the program always last more than the analysis period. The additional life thus obtained beyond the analysis period should be considered in some way in the economic analysis.

(9) The optimizing of one overlay for each initial design should be studied. This approach may give a wider selection of initial designs. A designer may care more for an initial design and plan to make final decisions regarding overlays later on.

(10) Several models developed for the working system are based on the concept that stress is a good predictor of performance. Validity of this assumption should be checked. The concept can be very helpful in evolving future modifications of the system.

(11) The importance of subbases should be established by more comprehensive models. The concept of the erodability factor should be expanded and more generalized correlations should be attempted.

(12) Alternative methods of optimization should be explored, including the possibilities of random programming techniques.

(13) A sensitivity analysis should be performed to ascertain the rationality of the computer program, to evaluate the relative effects of the variables being considered, and to set priorities for further research needs.

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APPENDIX 1

OPERATING MANUAL FOR PROGRAM RPS1

GUIDE FOR DATA INPUT FOR RPS1

with supplementary notes

extract from

A SYSTEMS ANALYSIS OF RIGID PAVEMENT DESIGN

by

Ramesh K. Kher, W. Ronald Hudson, and B. Frank McCullough

January 1971

RPS1 - GUIDE FOR DATA INPUT

RPS1 is a computer program which systematically designs rigid pavement structures. The development of equations, variables of design, and a working systems model have been discussed in various chapters of this report. This appendix is provided for the designer as a concise manual for the use of this program.

A summary flow diagram (Fig 11) describes the general procedure of design followed in the program. A problem number card at the beginning of each problem controls the start of the solution. The program works any number of problems in sequence unless a wrong or unacceptable data input causes an error in the solution process. The program finally terminates when a blank problem card is encountered.

Each problem consists of the following cards:

	Card Variables	Number of Cards
1.	Problem Number and Description	1
2.	Program Controls	1
3.	Traffic Volume	NL
4.	Traffic Growth and Distribution	1
5.	Designer's Restraints	1
6.	Performance Variables	1
7.	Traffic Delay	2
8.	Concrete Properties	NC
9.	Concrete Dimensions	1
10.	Subgrade Properties	1
11.	Subbase Properties	NSB
12.	Longitudinal and Transverse Bar Steel	2 (optional)
13.	Wire Mesh Reinforcement	1 (optional)
14.	Tie Bar Steel	1 (optional)

15.	Reinforcement Sizes	1
16.	Overlay Properties	1
17.	Seal Coat Data	1 (optional)
18.	Joint Data	1
19.	Maintenance, Dimensions and Miscellaneous Data	1

Values for NL, NC, and NSB should be carefully specified equal to the number of cards in each. Two cards of Item 12 should not be provided if only Mesh Reinforcement is to be designed (NCS3 = 2). Cards of Items 13 & 14 should not be provided if only bar reinforcement is to be designed (NCS3 = 1). The card of Item 17 should be omitted if asphalt concrete overlays are not to be designed. The above instructions must be followed strictly; otherwise, a wrong data input will result.

For a problem where both types of pavements, overlays, and reinforcements are to be designed, the total number of cards will be

$$18 + NL + NC + NSB$$

An average problem having, say, 25 axle ranges, two subbases, and two concretes to be tried, will have 47 cards for one problem. Figure 17 describes the assembly order for the RPS1 program deck with the data.

Guide for Data Input

The following pages provide a guide for data input comprising variable locations on the cards, their formats, definitions, and units. It is expected that these forms and instructions will be revised in the future with the new developments and modifications of the present version.

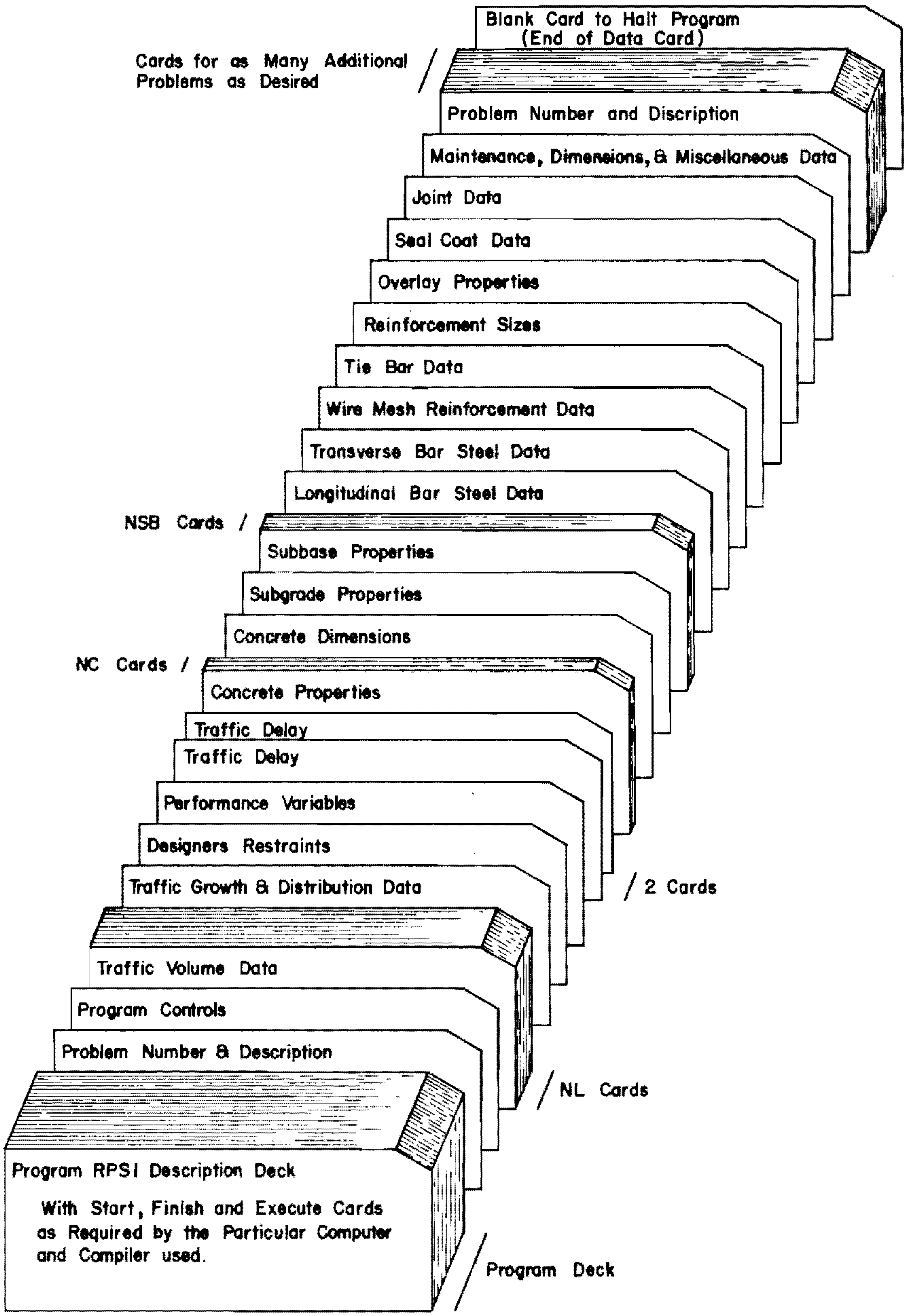

Fig 17. Assembly order for RPS1 program deck with data.

RPS1 - GUIDE FOR DATA INPUT

To become familiar with the data input and the program solutions, the user should refer to the example problem given in the report. Recoding and resolution of this example problem and the comparison of its input with the description of the real problem will prove to be very helpful in gaining practical experience and profiency in the use of the program.

RPS1 - GUIDE FOR DATA INPUT

PROBLEM IDENTIFICATION (one card)

NPROB	TITLE
A4	15 A4
1–4	

PROGRAM CONTROLS (one card)

NCS1	NCS2	NCS3		PSN1		PSN4
I10	I10	I10		F10.0		F10.0
1–10	20	30		41–50		71–80

OPERATION CONTROL SWITCHES

NCS1 decides the type of pavement to be designed

= 1 if only JC pavements to be designed

= 2 if only CRC pavements to be designed

Leave BLANK if both types of pavements to be tried

NCS2 decides the type of overlay to be designed

= 1 if only portland cement concrete overlay to be designed

= 2 if only asphalt concrete overlay to be designed

Leave BLANK if both types of overlay to be tried

NCS3 decides the type of reinforcement to be used

= 1 if only deformed bars to be used

= 2 if only welded wire meshes to be used

Leave BLANK if both types of reinforcement to be tried

RPS1 - GUIDE FOR DATA INPUT

PRINTING CONTROL SWITCHES

PSN1 decides whether to print the long or the short form of output

= 1 for short form of output

Leave BLANK for long form of output

PSN4 decides number of designs to be printed for summary table (six designs per page)

BLANK gives 12 designs

TRAFFIC VOLUME (NL cards)

NL	L1	L2	NCODE	NA
I10	I10	I10	F10.0	I10
1 10	20	30	40	50

L1	L2	NCODE	NA
I10	I10	F10.0	I10
11 20	30	40	50

NL - Number of Load Groups

L1-L2 - Range of Axle Loads

L1 is the lower value (pounds)
L2 is the upper value (pounds)

NCODE - Axle Code

= 1 for single axle
= 2 for tandem axle

NA - Number of Axles in the Range, both directions, per day

RPS1 - GUIDE FOR DATA INPUT

TRAFFIC GROWTH AND DISTRIBUTION (one card)

AGF	ADFGR		DDF	DFL		ADT
F10.0	F10.0		F10.0	F10.0		F10.0
1–10	11–20		31–40	41–50		61–70

AGF - Axle Growth Factor (percent per year)

ADTGR - ADT Growth Rate (percent per year)

DDF - Directional Distribution Factor (percent)

DFL - Lane Distribution Factor (percent)

ADT - Initial ADT Expected, one direction (vehicles per day)

DESIGNER'S RESTRAINTS (one card)

CMAX	TMAX	OFMIN	BOMIN	OMAXA	OMINA	OMAXC	OMINC	AP
F10.0	F10.0	F10.0	F10.0	F5.0	F5.0	F5.0	F5.0	F10.0
1–10	11–20	21–30	31–40	41–45	46–50	51–55	56–60	61–70

CMAX - Maximum Funds Available for Initial Construction (dollars)

TMAX - Maximum Allowable Thickness of Slab plus Subbase (inches)

OFMIN - Minimum Allowable Time to the First Overlay (years)

BOMIN - Minimum Allowable Time Between Overlays (years)

OMAXA - Maximum Total AC Overlay Thickness (inches)

OMINA - Minimum AC Overlay Thickness at One Time (inches)

OMAXC - Maximum Total PCC Overlay Thickness (inches)

OMINC - Minimum PCC Overlay Thickness at One Time (inches)

AP - Length of Analysis Period (years)

RPS1 - GUIDE FOR DATA INPUT

PERFORMANCE VARIABLES (one card)

P1	P2	POV	P2P	BONE
F10.0	F10.0	F10.0	F10.0	F10.0

Card columns: 1, 10, 20, 30, 40, 50

P1 - Initial Serviceability Index

P2 - Terminal Serviceability Index

POV - Serviceability Index After an Overlay

P2P - Lower Bound on the Serviceability Index Due to Swelling Clay for Zero Traffic and Infinite Time

BONE - Swelling Clay Parameter

TRAFFIC DELAY VARIABLES (two cards)

DTSO	DTSN	DDOZ	PAPH	HPDC	NOLO	NOLN		ITYPE
F10.0	F10.0	F10.0	F10.0	F10.0	I5	I5		F10.0

Card columns: 1, 10, 20, 30, 40, 50, 55, 60, 71, 80

DTSO - Distance Over Which Traffic is Slowed in Overlay Direction (miles)

DTSN - Distance Over Which Traffic is Slowed in Non-Overlay Direction (miles)

DDOZ - Distance Measured Along Detour Around Overlay Zone (miles)

PAPH - Percent of ADT Arriving Each Hour of Construction

HPDC - Number of Hours Per Day that Overlay Construction Takes Place

NOLO - Number of Open Lanes in Restricted Zone, Overlay Direction

NOLN - Number of Open Lanes in Restricted Zone, Non-Overlay Direction

ITYPE - 1 for Rural Roads
2 for Urban Roads

RPS1 - GUIDE FOR DATA INPUT

PVSO	PVSN	DEQO	DEQN	AAS	ASOD	ASND	MODEL
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	I10
1–10	20	30	40	50	60	70	80

PVSO - Vehicles Stopped by Construction Equipment and Personnel, Overlay Direction (percent)

PVSN - Vehicles Stopped by Construction Equipment and Personnel, Non-Overlay Direction (percent)

DEQO - Average Delay Per Vehicle Stopped by Road Equipment and Personnel, Overlay Direction (hours)

DEQN - Average Delay Per Vehicle Stopped by Road Equipment and Personnel, Non-Overlay Direction (hours)

AAS - Average Approach Speed to Overlay Area (mph)

ASOD - Average Speed Through Restricted Zone, Overlay Direction (mph)

ASND - Average Speed Through Restricted Zone, Non-Overlay Direction (mph)

MODEL - Model Number Describing the Traffic Situation During Overlay Construction

CONCRETE (NC cards)

NC	ND	NP	SX	SXSD	SXCL	WC	E	TS	CIC	CPCYC	CSC
I5	I3	I2	F5.0	F5.0	F5.0	F5.0	F10.0	F10.0	F10.0	F10.0	F10.0
1–5	8	10	15	20	25	30	40	50	60	70	80

ND	NP	SX	SXSD	SXCL	WC	E	TS	CIC	CPCYC	CSC
I3	I2	F5.0	F5.0	F5.0	F5.0	F10.0	F10.0	F10.0	F10.0	F10.0
6–8	10	15	20	25	30	40	50	60	70	80

NC - Number of Concrete Types

ND - Number of Days at Which Concrete Flexural Strength Measured

NP - 1 for Flexural Strength Obtained by Center Point Loading
2 for Flexural Strength Obtained by Third Point Loading

SX - Concrete Flexural Strength, Mean Value (psi)

RPS1 - GUIDE FOR DATA INPUT

SXSD - Concrete Flexural Strength, Standard Deviation (psi)

SXCL - Concrete Flexural Strength, Confidence Level (percent)

WC - Weight of Concrete (pounds per cubic foot)

E - Modulus of Elasticity at 28 Days (psi)

TS - Tensile Strength of Concrete (psi)

CIC - Initial Construction Equipment Cost per Lane Mile for Pouring Concrete (dollars)

CPCYC - Cost per Cubic Yard of Concrete (dollars)

CSC - Cost per Lane Mile of Surfacing Concrete for Finish, Texture, and Curing (dollars)

CONCRETE DIMENSIONS (one card)

Columns	11–20	21–30	31–40
Variable	TCMIN	TCMAX	CINC
Format	F10.0	F10.0	F10.0

TCMIN - Minimum Allowable Concrete Thickness (inches)

TCMAX - Maximum Allowable Concrete Thickness (inches)

CINC - Pratical Increment at Which Concrete Can Be Easily Poured or the Increment at Which the Solutions Should Be Tried, whichever is larger

SUBGRADE (one card)

Columns	1–10	11–20	21–30	31–40	41–50	51–60	61–65	66–70	71–80
Variable	SGK	SGKSD	SGKCL	TTC	TTCSD	TTCCL	FFSG	EFSG	CPLMSG
Format	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F5.0	F5.0	F10.0

SGK - Subgrade k, Mean Value (pci)

SGKSD - Subgrade k, Standard Deviation (pci)

SGKCL - Subgrade k, Confidence Level (percent)

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- TTC - Texas Triaxial Class, Mean Value
- TTCSD - Texas Triaxial Class, Standard Deviation
- TTCCL - Texas Triaxial Class, Confidence Level (percent)
- FFSG - Friction Factor Between Subgrade and Concrete
- EFSG - Subgrade Erodability Factor
- CPLMSG - Cost per Lane Mile of Subgrade Preparation (dollars)

SUBBASE (NSB cards)

NSB	NAME	EF	FFSB	TTCS	ES	CIS	CPCYS	TSMIN	TSMAX	SINC
I5	2A4,A2	F5.0	F5.0	F5.0	F10.0	F10.0	F10.0	F5.0	F5.0	F5.0
1–5	15	21–25	30	35	45	55	65	70	75	70

NAME	EF	FFSB	TTCS	ES	CIS	CPCYS	TSMIN	TSMAX	SINC
2A4,A2	F5.0	F5.0	F5.0	F10.0	F10.0	F10.0	F5.0	F5.0	F5.0
6–15	21–25	30	35	45	55	65	70	75	70

- NSB - Number of Subbase Types
- NAME - Description of Subbase
- EF - Erodability Factor for Subbase
- FFSB - Friction Factor Between Subbase and Concrete
- TTCS - Texas Triaxial Class for Subbase
- ES - Subbase Material Modulus Value (psi)
- CIS - Initial Construction Equipment Cost per Lane Mile for Subbase Construction
- CPCYS - Cost per Cubic Yard of Compacted Subbase
- TSMIN - Minimum Allowable Subbase Thickness (inches)
- TSMAX - Maximum Allowable Subbase Thickness (inches)
- SINC - Practical Increments at Which Subbase Can Easily be Poured or the Solutions be Tried

BAR STEEL - LONGITUDINAL (this card only if NCS3 is not 2)

NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS
2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0
1 – 10	15	20	30	35	40	50	55	60	70	75	80

NAMEBS - Bar Steel Identification Number

TYSBS - Tensile Yield Point Strength of Steel (psi)

CPPBS - Cost per Pound of Bar Steel (dollars per pound)

BAR STEEL - TRANSVERSE (this card only if NCS3 is not 2)

NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS	NAMEBS	TYSBS	CPPBS
2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0
1 – 10	15	20	30	35	40	50	55	60	70	75	80

NAMEBS - Bar Steel Identification Number

TYSBS - Tensile Yield Point Strength of Steel (psi)

CPPBS - Cost per Pound of Bar Steel (dollars per pound)

WIRE MESH (this card only if NCS3 is not 1)

NAMEWS	TWSWS	CPPWS	NAMEWS	TYSWS	CPPWS	NAMEWS	TYSWS	CPPWS	NAMEWS	TYSWS	CPPWS
2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0
1 – 10	15	20	30	35	40	50	55	60	70	75	80

NAMEWS - Wire Mesh Steel Identification Number

TYSWS - Tensile Yield Point Strength of Steel (psi)

CPPWS - Cost per Pound of Wire Mesh Steel (dollars per pound)

TIE BAR STEEL (this card only if NCS3 is not 1)

NAMETS	TYSTS	CPPTS	NAMETS	TYSTS	CPPTS	NAMETS	TYSTS	CPPTS	NAMETS	TYSTS	CPPTS
2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0	2A4,A2	F5.0	F5.0
1–10	15	20	30	35	40	50	55	60	70	75	80

NAMETS - Tie Bar Steel Identification Number

TYSTS - Tensile Yield Point Strength of Tie Bar Steel (psi)

CPPTS - Cost per Pound of Tie Bar Steel (dollars per pound)

STEEL SIZES (one card)

BARN 4 values				SL(1)	ST(1)	SL(2)	ST(2)	SL(3)	ST(3)	SL(4)	ST(4)	TBARN 4 values			
F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	F5.0
1–5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80

BARN - Bar Numbers to be Tried
Give only if NCS3 = 0 or = 1

MESHES - Mesh Sizes to be Tried
Give only if NCS3 = 0 or = 2
SL is Spacing of Longitudinal Wires
ST is Spacing of Transverse Wires

TBARN - Tie Bar Numbers to be Tried
Give only if NCS3 = 0 or = 2

OVERLAYS (one card)

CIOV	CPCYAC	ACE	ACPR		CPR	COEF	CPSYR
F10.0	F10.0	F10.0	F10.0		F10.0	F10.0	F10.0
1–10	20	30	40		51–60	70	80

CIOV - Initial Construction Equipment Cost per Lane Mile for AC Overlays

CPCYAC - Cost per Cubic Yard of In-Place Compacted Asphalt Concrete

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ACE - Asphalt Concrete Modulus Value

ACPR - Production Rate of Compacted Asphalt Concrete (cubic yards per hour)

CPR - Concrete Production Rate (cubic yards per hour)

COEF - Concrete Coefficient for Corps of Engineers Formula (Eq 4.30)

CPSYR - Any Additional Cost per Square Yard for Overlay Construction (present value)

SEAL COATS (this card only if NCS2 is not 1)

TFS	TBS	CPLMS
F10.0	F10.0	F10.0
1–10	20	30

TFS - Minimum Time for First Seal Coat After an Asphalt Concrete Overlay

TBS - Minimum Time Between Seal Coats

CPLMS - Cost per Lane Mile of a Seal Coat

JOINTS (one card)

CPFTJ	CPFLJ		SLV	SUV		NJM
F10.0	F10.0		F10.0	F10.0		I10.0
1–10	20		31–40	50		61–70

CPFTJ - Cost per Foot of Transverse Joint (dowels, sawing, sealing, etc.)

CPFLJ - Cost per Foot of Longitudinal Joint (excluding cost of the bars)

SLV - Joint Spacing to be Tried for JCP Pavements, lower value

SUV - Joint Spacing to be Tried for JCP Pavements, upper value

NJM - Number of Transverse Construction or Warping Joints per Mile Provided for CRCP Pavements (if any)

RPS1 - GUIDE FOR DATA INPUT

MAINTENANCE, DIMENSIONS, AND MISCELLANEOUS (one card)

DFTY	CLW	CERR	CMAT	RINT	PSVGE	WL	NLT
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	I10
1 10	20	30	40	50	60	70	80

DFTY - Days of Freezing Temperature per Year

CLW - Composite Labor Wage (dollars per unit maintenance)

CERR - Composite Equipment Rental Rate (dollars per unit maintenance)

CMAT - Cost of Materials (dollars per unit maintenance)

RINT - Rate of Interest or Time Value of Money (percent per year)

PSVGE - Salvage Percent of Structural Value at the End of Analysis Period

WL - Width of Each Lane (feet)

NLT - Total Number of Lanes in Both Directions

BLANK CARD TO TERMINATE THE PROGRAM

GENERAL PROGRAM NOTES

Program Controls:

These optional parameters are built in to obtain various options for designing particular types of rigid pavements, overlays, and reinforcements. If all NCS switches are left BLANK, the program designs and optimizes out of all possible types of solutions.

NCS1 and NCS2 can very effectively be used to decrease the computational time in case a particular type of design is not required.

NCS3 can be used to design a particular type of reinforcement if desired, but a BLANK for NCS3 will select the most economical type of reinforcement out of bar steels and wire meshes.

A BLANK for PSN4 automatically gives 12 designs for the Summary Table. The program is at present dimensioned for a maximum of 24 designs and, because a number greater than 24 can produce serious errors in the design process, PSN4 is assumed to be 24 if a larger number is input. In case the program generates less designs than the number specified, the program prints for the Summary Table as many designs as generated.

The program requires a storage of about 105,000 octal with dimensions for 24 design strategies. The storage will increase if the program is redimensioned.

Traffic Data:

The number of load ranges in traffic data should be enough to reasonably divide the axle loads in various groups. The average value of a load range is used to compute equivalent loads and, therefore, traffic analysis gets more accurate with an increasing number of load ranges. If it is observed that a particular axle load is considerably more frequent than the other loads in a range, the load should be changed into a load group by itself. There is no limit on the maximum number of load groups. Frequency of loads, NA, is the average daily axles in both directions. The values should be as accurate as possible because these data are projected over the entire analysis period.

Traffic Growth and Distribution:

The growth factors are linear percent increases per year; e.g., a growth factor of x percent per year for average daily traffic, X, will make it $X + \frac{xY}{100}$ after Y years. Average daily traffic should be given in one direction.

Designer's Restraints:

These inputs should be specified very carefully. For a set of very restrictive values, these restraints may reject certain desirable designs, but also certain other values of these restraints may help generate a large number of designs requiring a high amount of computational time.

A complete analysis of the effects of these restrictions is printed for every problem on the last page. If this analysis shows that a considerable proportion of designs is being rejected due to a particular restriction being relatively too strong, and if the designer feels that some of the optimal designs may be lost because of this, the problem should be run again with the restriction a little more open.

Minimum overlay thicknesses should generally be specified according to the general practices. Maximum total initial thickness will become a restriction when its value is less than the sum of maximum concrete and subbase thicknesses. A zero value of minimum time to the first overlay will remove this restriction from the program.

Maximum total overlay thickness values should be specified with care. The difference of maximum and minimum overlay thickness generally determines the amount of computational work involved in an overlay subsystem. A high value may sometimes lead to very large overall computation time.

Performance Variables:

In view of the statistical development of performance models used in the program, it is desirable that P1 not be greater than 4.5 and P2 not be less than 1.5. Due to the basic assumptions, P2P should always be less than or equal to P2.

Traffic Delay Variables:

These variables determine the indirect costs due to traffic delay during overlay construction. All inputs should conform to the MODEL specified for handling traffic during the overlay. Detour distance, DDOZ, is not required unless Model 5 is used for handling traffic. The product of PAPH and HPDC should not be greater than 100.

The program is designed to overlay one lane at a time. The number of open lanes in the overlay or nonoverlay direction should not be greater than three. Data built into the program do not allow the vehicle speeds of more than 60 mph and this value is adopted if higher speeds are input.

Materials (concrete):

The program is presently dimensioned for a maximum of six types of concrete which can be specified. The program converts the value of flexural strength if ND = 7 and/or NP = 1 . Standard deviation and confidence level can be left BLANK if values are not known. In that case, the program will use the mean value of flexural strength, SX.

A value for SXCL must be given in case a value for SXSD is specified.

TS can be left BLANK if not known. A value of 0.4 times the design value of flexural strength will be used if TS is BLANK.

Flexural strength, SX, should not contain any factor of safety to design. This factor is already built into the performance model.

Concrete Dimensions:

The minimum and maximum values should be specified carefully based on experience. Increment value, CINC, should be decided by the construction equipments to be used and general practices followed. Any value of this increment can be specified. A value of 1.0 inch is used in case CINC is left BLANK. These values are used for every type of concrete input.

Subgrade:

The options of specifying mean subgrade modulus of reaction, SGK, or its mean Texas Triaxial Class, TTC, are available. In case both the values are given, the program will use the modulus value. Standard deviations and confidence levels can be left BLANK if not known. The program will use the mean values in such cases. Confidence levels must be given in case values for standard deviations are input. The friction factor and erodability factor for subgrade may not be given if no solutions with the slab directly resting on the subgrade are to be generated.

Materials (subbase):

The program is presently dimensioned for specifying a maximum of four different types of subbases. The option of specifying either the modulus values of subbase materials or their Texas Triaxial Class values is built in the program. Modulus value will be used in case both the properties are input. The minimum, maximum, and increment values for each subbase can be specified separately. Increment values should be specified based on the general practices followed for constructing subbases.

Materials (steels):

Bar Steels:

These two cards for longitudinal and transverse bar steels should be provided if NCS3 is not equal to 2, i.e., if only bars are to be designed or if bars and wire meshes both are to be tried. A maximum of four types of bar steels for longitudinal reinforcement and the same number for transverse reinforcement can be specified. Tensile yield point strength should not contain any factor of safety. A value has been built into the program for this.

Wire Meshes:

This card should not be provided if NCS3 is equal to 1. A maximum of four types of wire mesh steels can be input. Tensile yield point strength should not contain any safety factor.

Tie Bars:

These data are used for providing tie bars whenever wire meshes are designed. This card, therefore, should not be provided when only bar reinforcement is specified to be designed, i.e., NCS3 = 1. In a case when bar reinforcement is designed, tie bars will be provided of the same steel as used for transverse reinforcement bars.

Steel Sizes:

This card contains the inputs for determining the layout configuration for reinforcement and tie bars. A maximum of four bar numbers can be input for determining the spacing of bar steels in case bar reinforcement is provided for the design. In case of wire meshes, pairs of longitudinal and transverse mesh spacings are input and corresponding diameters of meshes to be used for the design are computed and printed. A maximum of four pairs can be specified.

In a case when wire meshes are intended to be designed, bar sizes to be used as tie bars should be specified. A maximum of four sizes can be specified for tie bars. For designs for which bar reinforcement is provided, the same sizes will be tried for tie bars as are used for designing transverse bar steel.

In every case, the program gives the spacing of tie bars along the longitudinal joints. The lengths of tie bars is 60 times the diameter being provided.

The spaces for these steel sizes can be left blank for those types which will not be used in the design according to NCS3 switch. Bar numbers, BARN ( ), may not be provided if NCS3 = 2 and, vice versa, the wire mesh spacings SL ( ) and ST ( ) and tie bar numbers, TBARN ( ), may not be provided if NCS3 = 1.

Materials (overlay):

This card contains inputs for both types of overlays, but the values may be left BLANK if one is not to be used according to NCS2 switch. CIOV, CPCYAC, ACE, and ACPR may be left BLANK if only PCC overlays are to be designed and, vice versa, CPR and COEF can be left BLANK if only AC overlays are desired. CPSYR is a random additional cost and is built in the program to give the designer an option of adding a particular cost to all the designs. A designer may add any such initial or the present value of a future cost which is not taken into account in the program and is advocated by the special conditions of a site.

Seal Coats:

This card should not be provided if only portland cement concrete overlays are to be designed, i.e., when NCS2 = 1. Seal coats are only provided on those pavements which are provided with asphalt concrete overlays.

Joints:

Cost per foot of transverse joints, CPFTJ, should include the cost of sealing and dowels. Cost per foot of longitudinal joints should not include the cost of tie bars. SLV and SLU are the lower and upper values of transverse joint spacings to be used for jointed concrete pavements. The program determines the most economical spacing of these joints. NJM is provided in case some transverse joints are desired for CRC pavements; e.g., construction joints or warping joints.

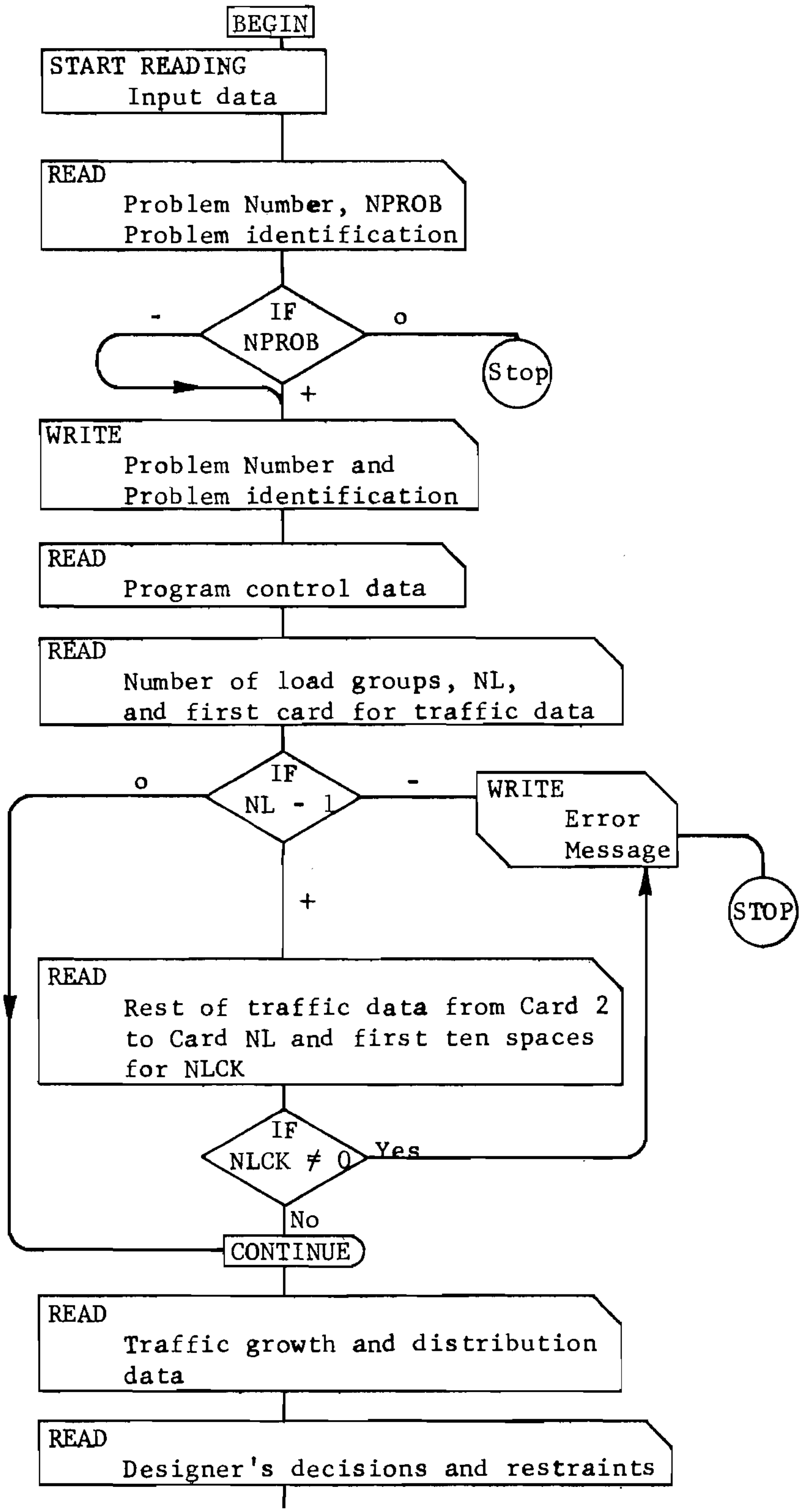
Maintenance, Dimensions, and Miscellaneous:

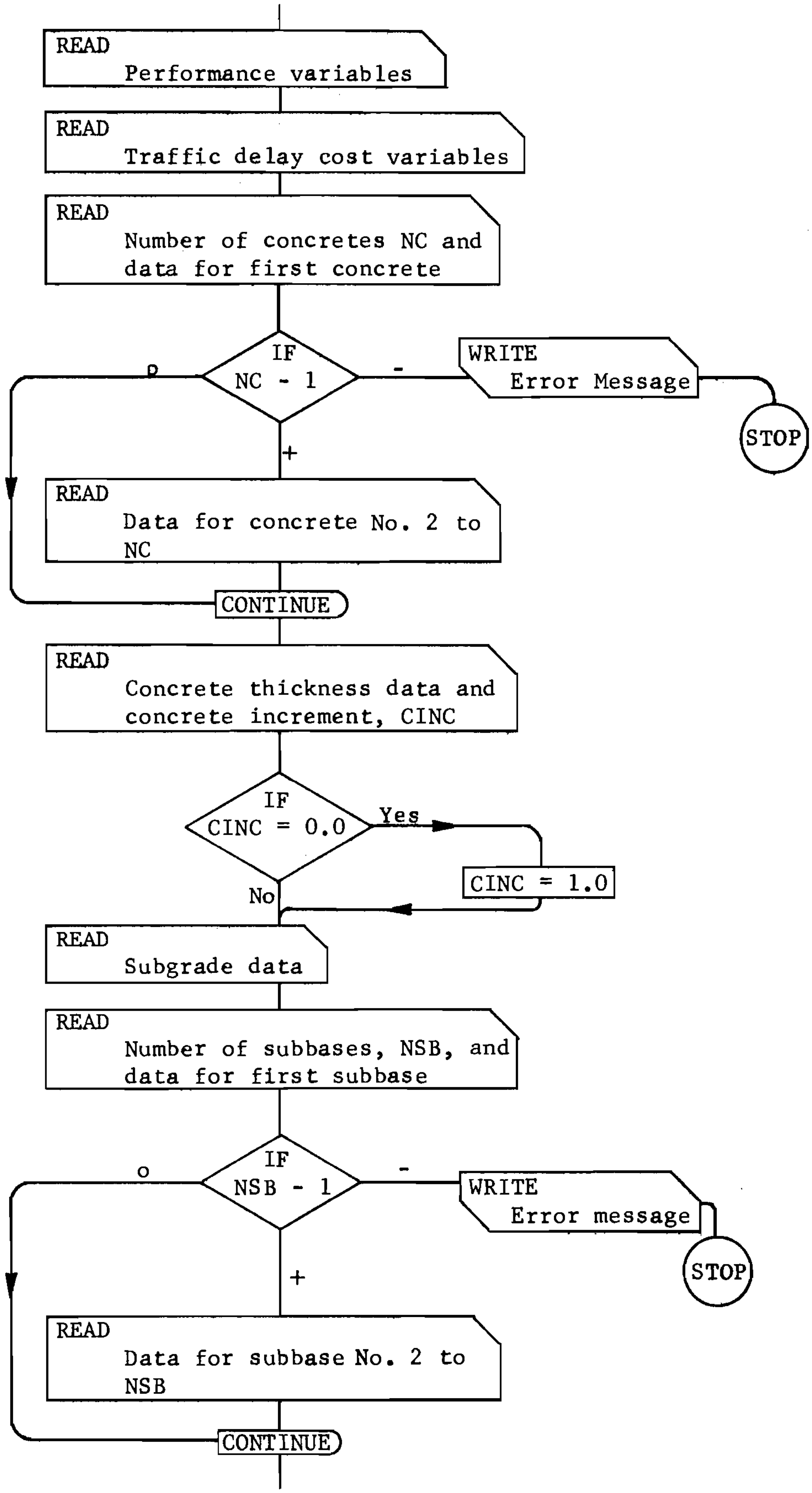
For complete explanations of maintenance cost variables, CLW, CERR, and CMAT, refer to NCHRP Report 42 (Ref 62). Interest rate is a very important variable of design and determines the present value of all future costs. A zero value for interest rate eliminates this factor. The total number of lanes, NLT, should conform to the traffic MODEL used and other inputs specified for traffic delay variables. If the road is to be abandoned at the end of the analysis period, zero value for PSVGE should be specified.

APPENDIX 2

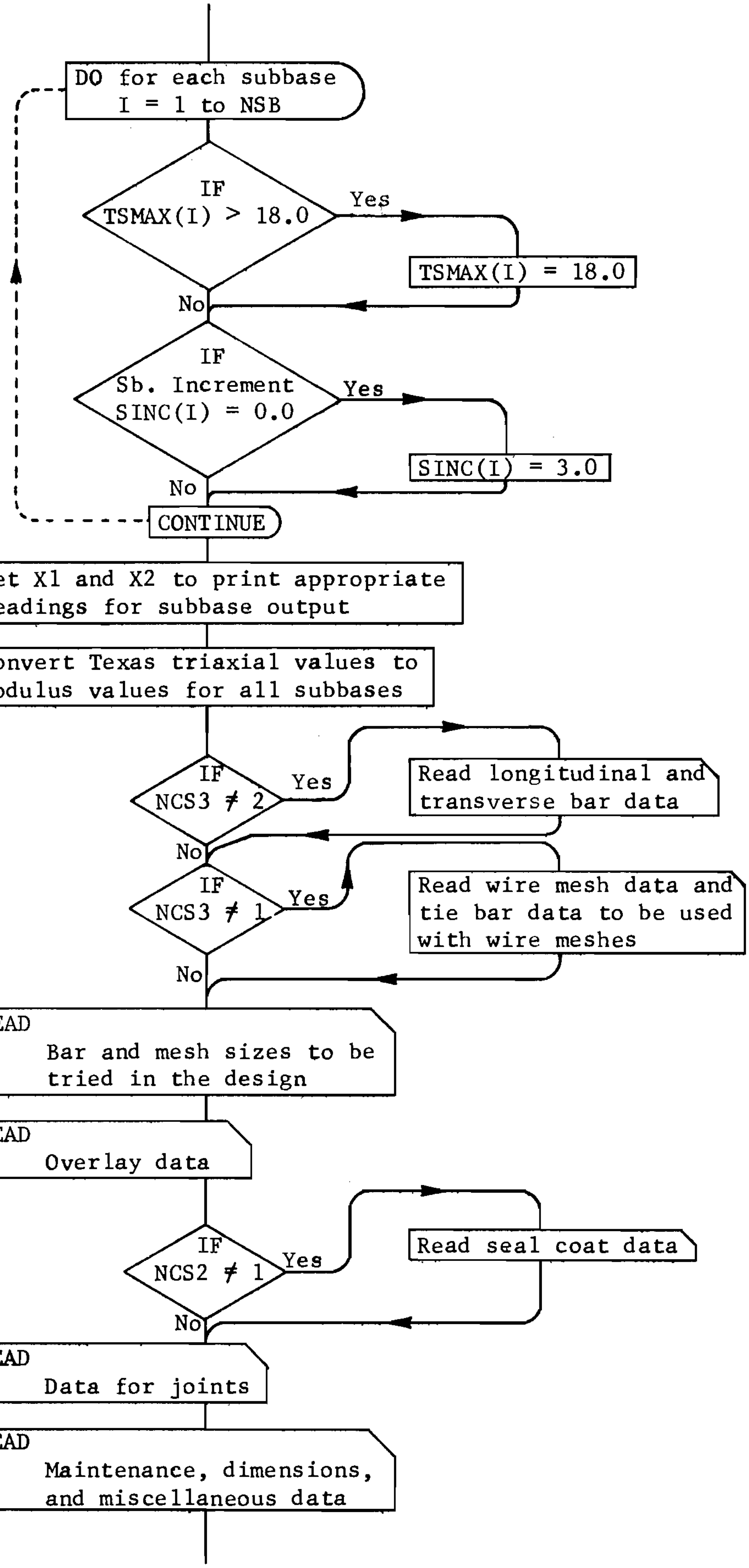
GENERAL FLOW DIAGRAM FOR PROGRAM RPS1

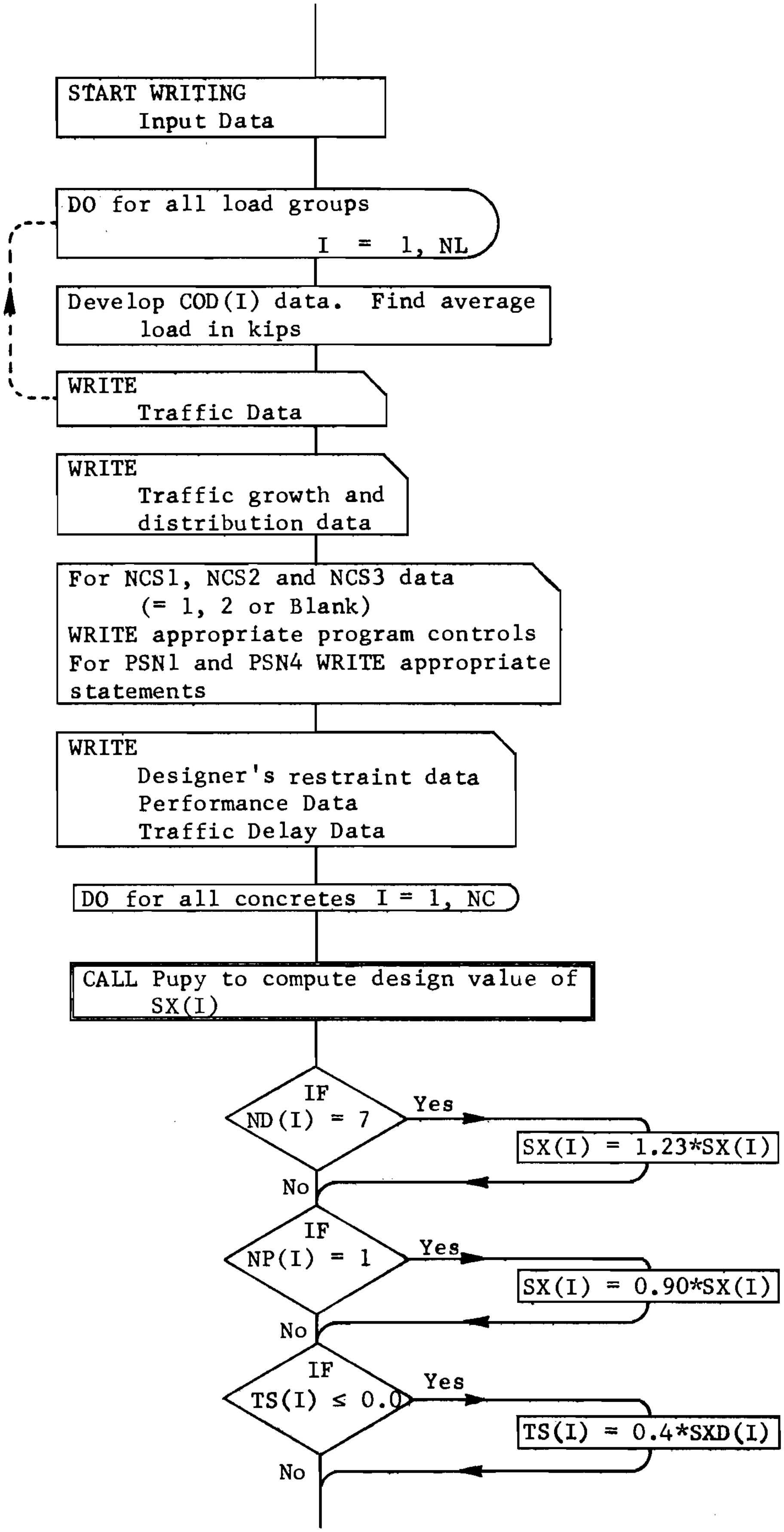
GENERAL FLOW DIAGRAM FOR PROGRAM RPS1

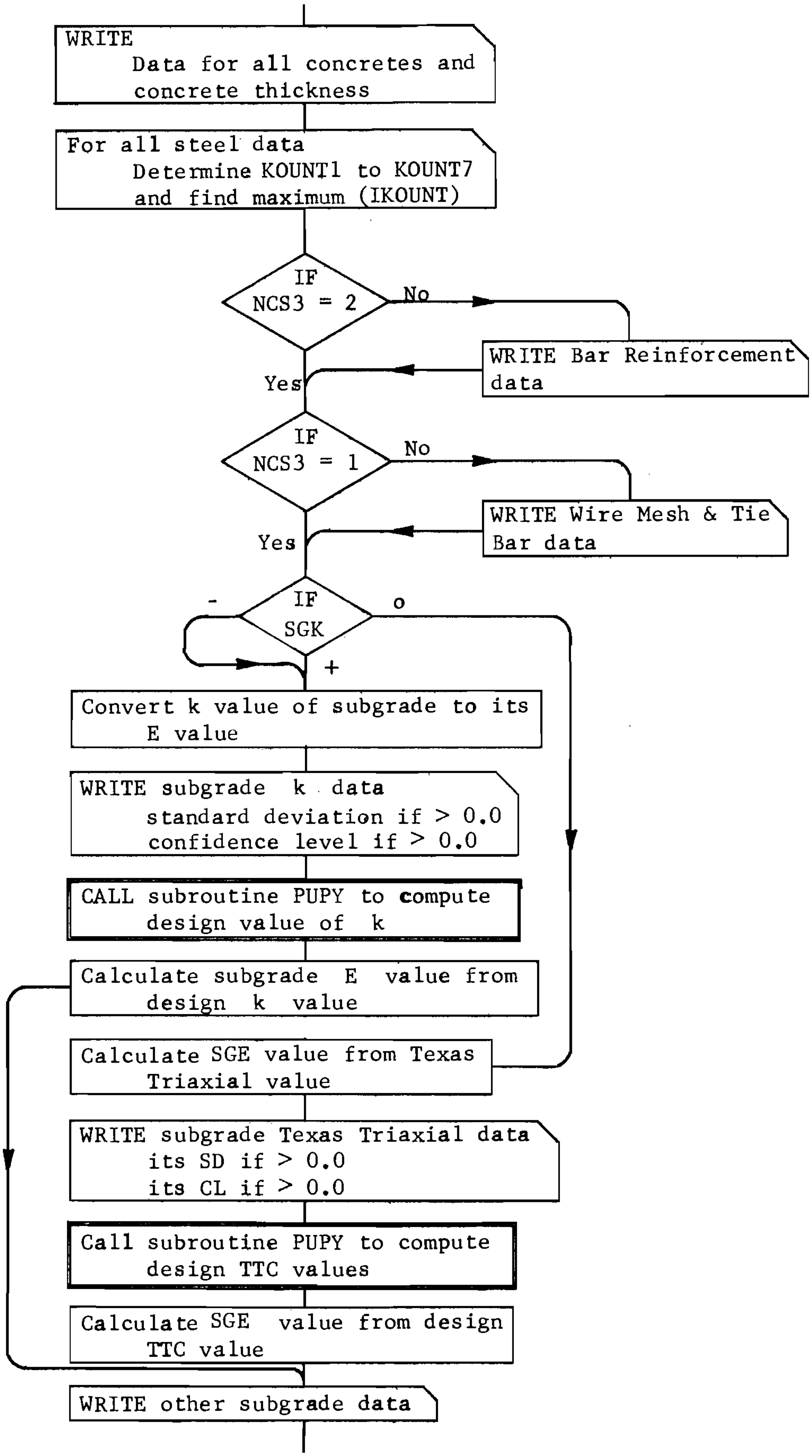


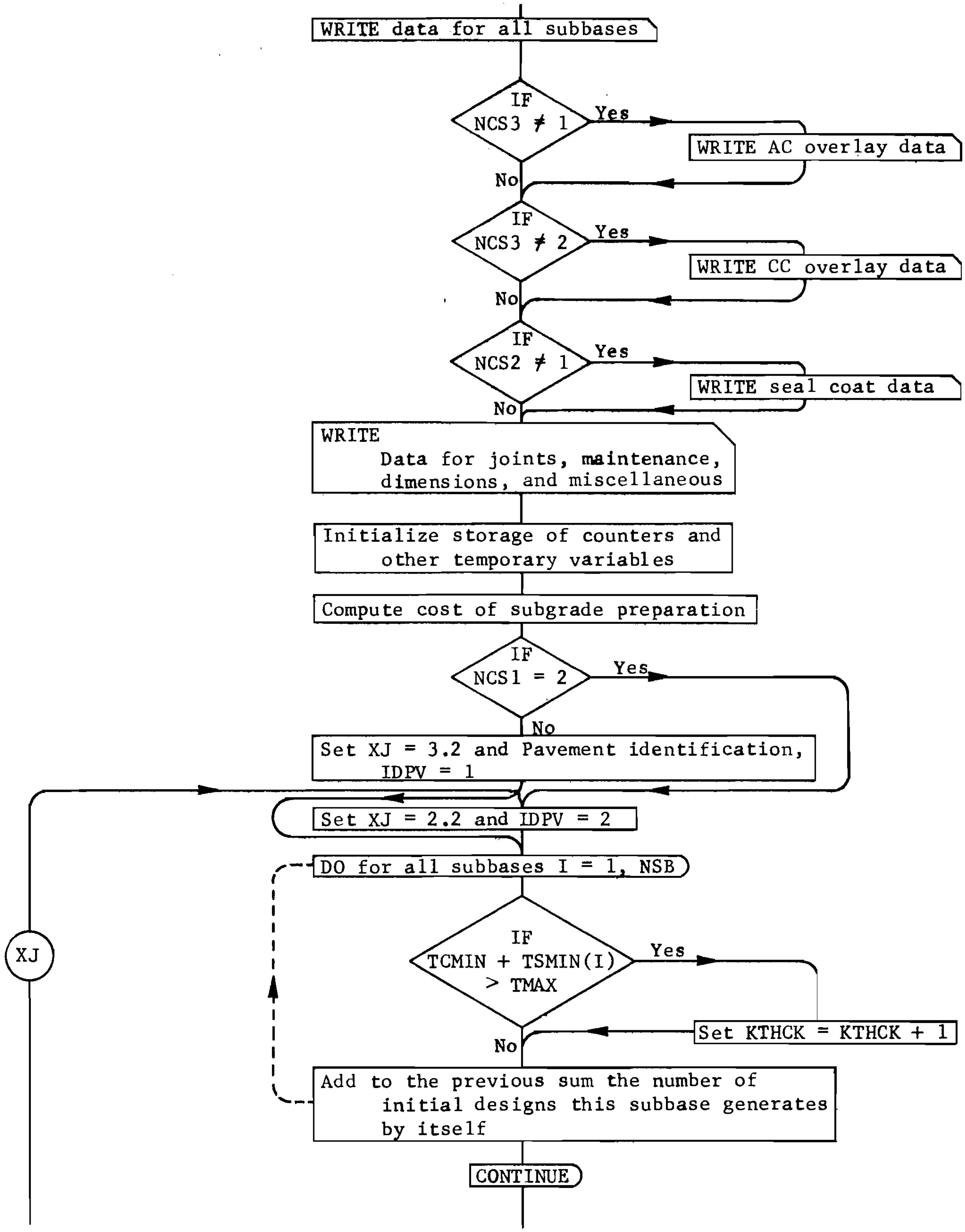


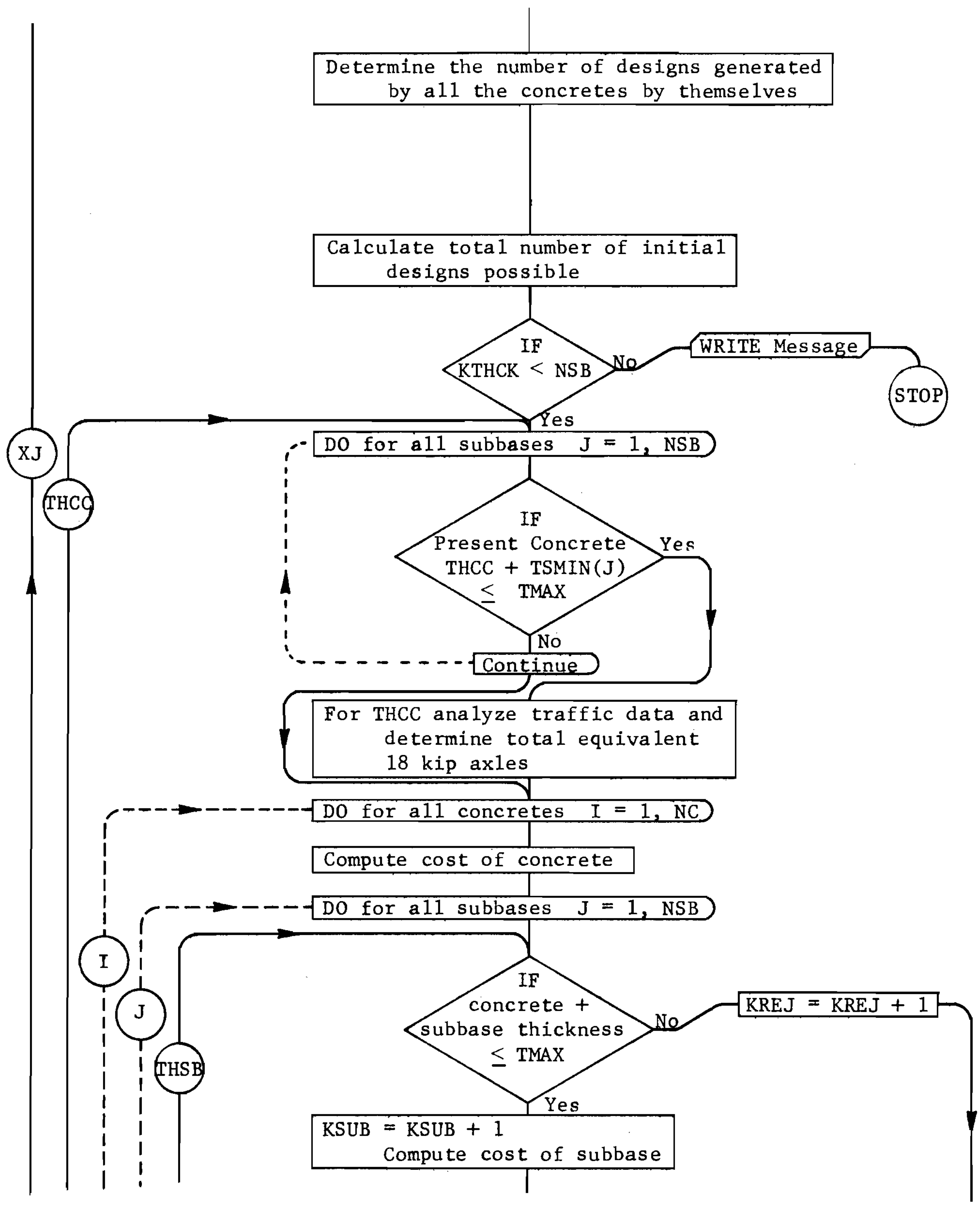
READ
Performance variables
READ
Traffic delay cost variables
READ
Number of concretes NC and data for first concrete
IF
NC - 1
0
-
+
WRITE
Error Message
STOP
READ
Data for concrete No. 2 to NC
CONTINUE
READ
Concrete thickness data and concrete increment, CINC
IF
CINC = 0.0
Yes
No
CINC = 1.0
READ
Subgrade data
READ
Number of subbases, NSB, and data for first subbase
IF
NSB - 1
o
-
+
WRITE
Error message
STOP
READ
Data for subbase No. 2 to NSB
CONTINUE

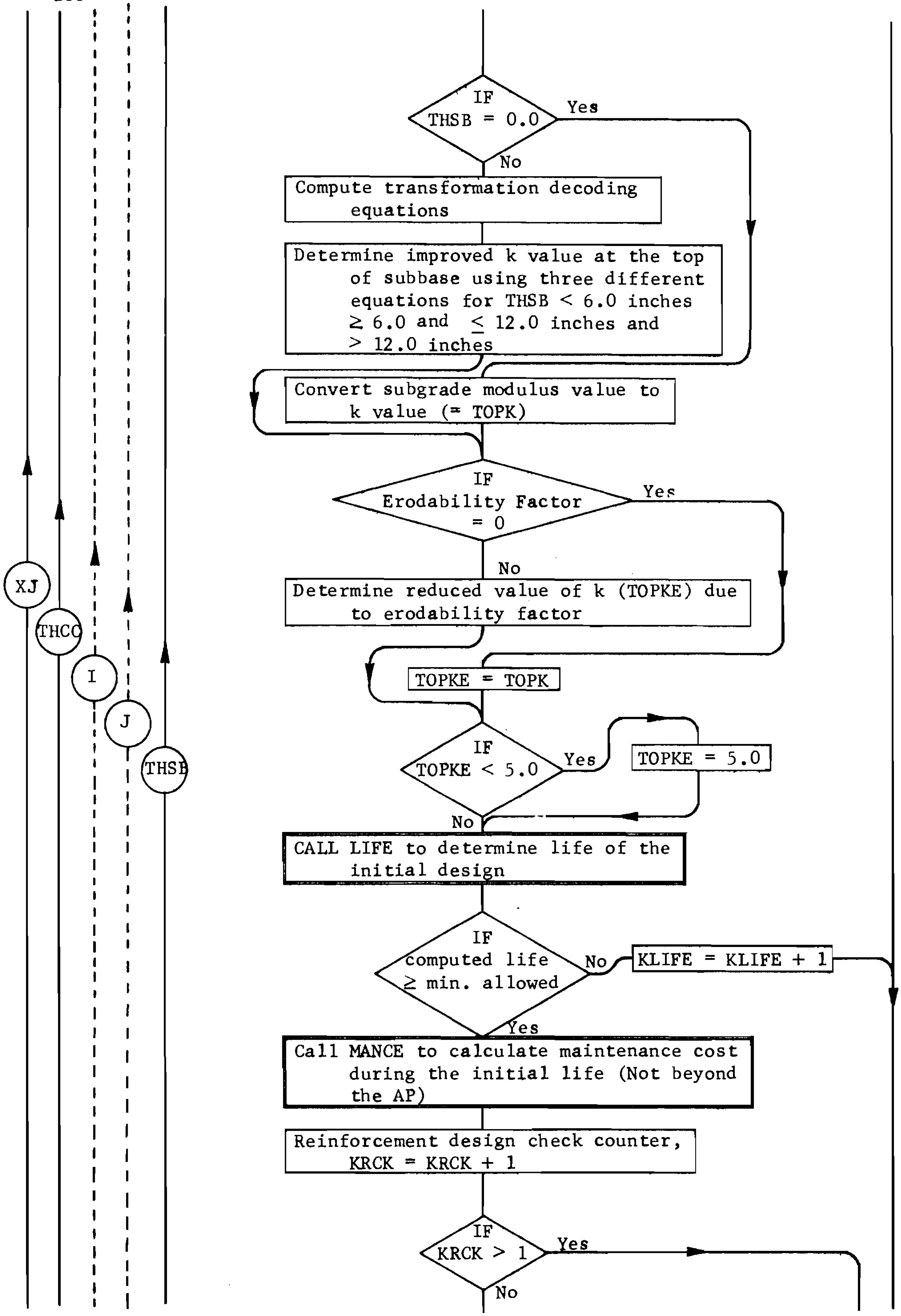

DO for each subbase
I = 1 to NSB
IF
TSMAX(I) > 18.0
Yes
TSMAX(I) = 18.0
No
IF
Sb. Increment
SINC(I) = 0.0
Yes
SINC(I) = 3.0
No
CONTINUE
Set X1 and X2 to print appropriate headings for subbase output
Convert Texas triaxial values to modulus values for all subbases
IF
NCS3 ≠ 2
Yes
Read longitudinal and transverse bar data
No
IF
NCS3 ≠ 1
Yes
Read wire mesh data and tie bar data to be used with wire meshes
No
READ
Bar and mesh sizes to be tried in the design
READ
Overlay data
IF
NCS2 ≠ 1
Yes
Read seal coat data
No
READ
Data for joints
READ
Maintenance, dimensions, and miscellaneous data

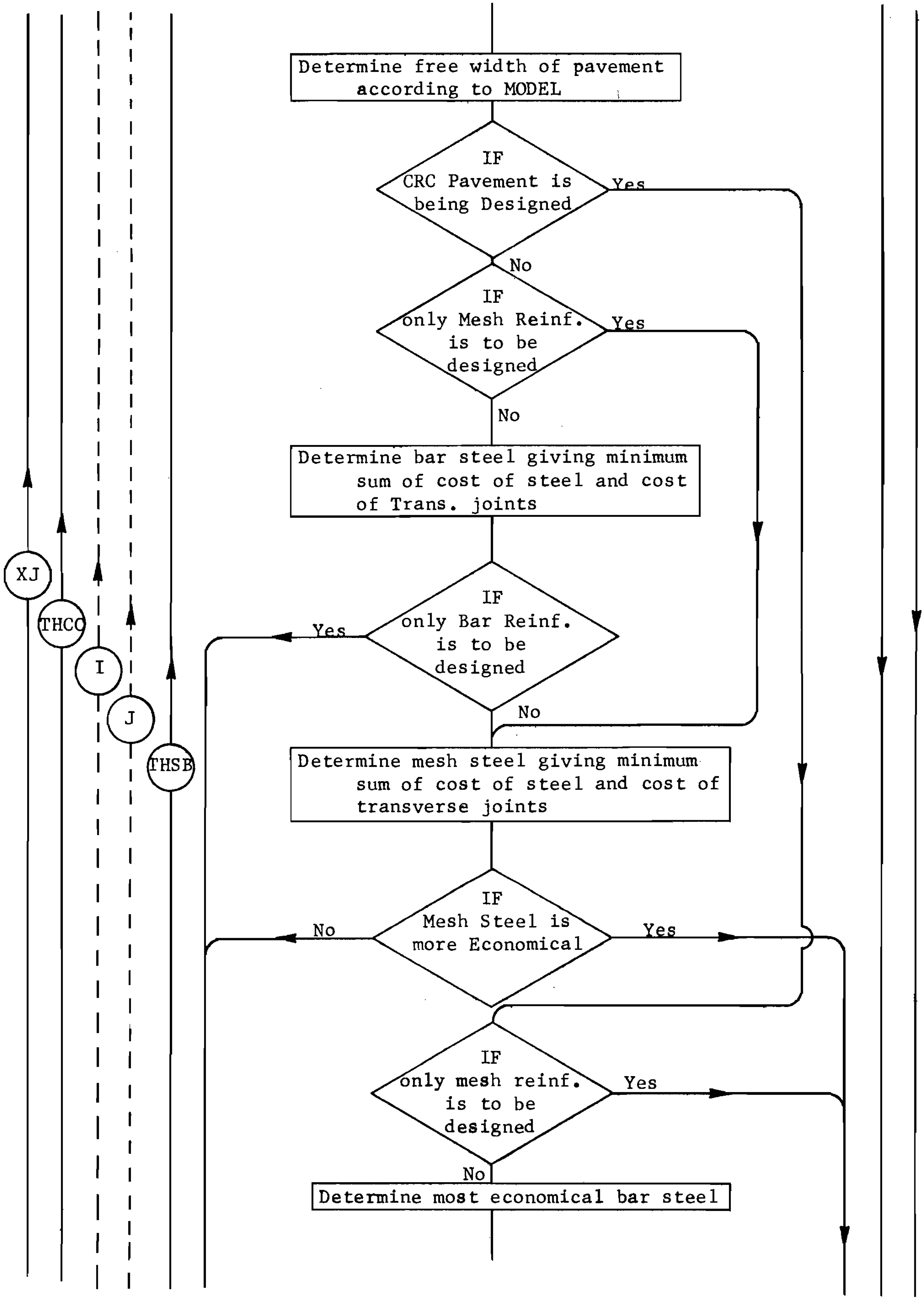

START WRITING Input Data
DO for all load groups I = 1, NL
Develop COD(I) data. Find average load in kips
WRITE Traffic Data
WRITE Traffic growth and distribution data
For NCS1, NCS2 and NCS3 data (= 1, 2 or Blank)
WRITE appropriate program controls
For PSN1 and PSN4 WRITE appropriate statements
WRITE Designer's restraint data
Performance Data
Traffic Delay Data
DO for all concretes I = 1, NC
CALL Pupy to compute design value of SX(I)
IF ND(I) = 7
Yes
SX(I) = 1.23*SX(I)
No
IF NP(I) = 1
Yes
SX(I) = 0.90*SX(I)
No
IF TS(I) ≤ 0.0
Yes
TS(I) = 0.4*SXD(I)
No

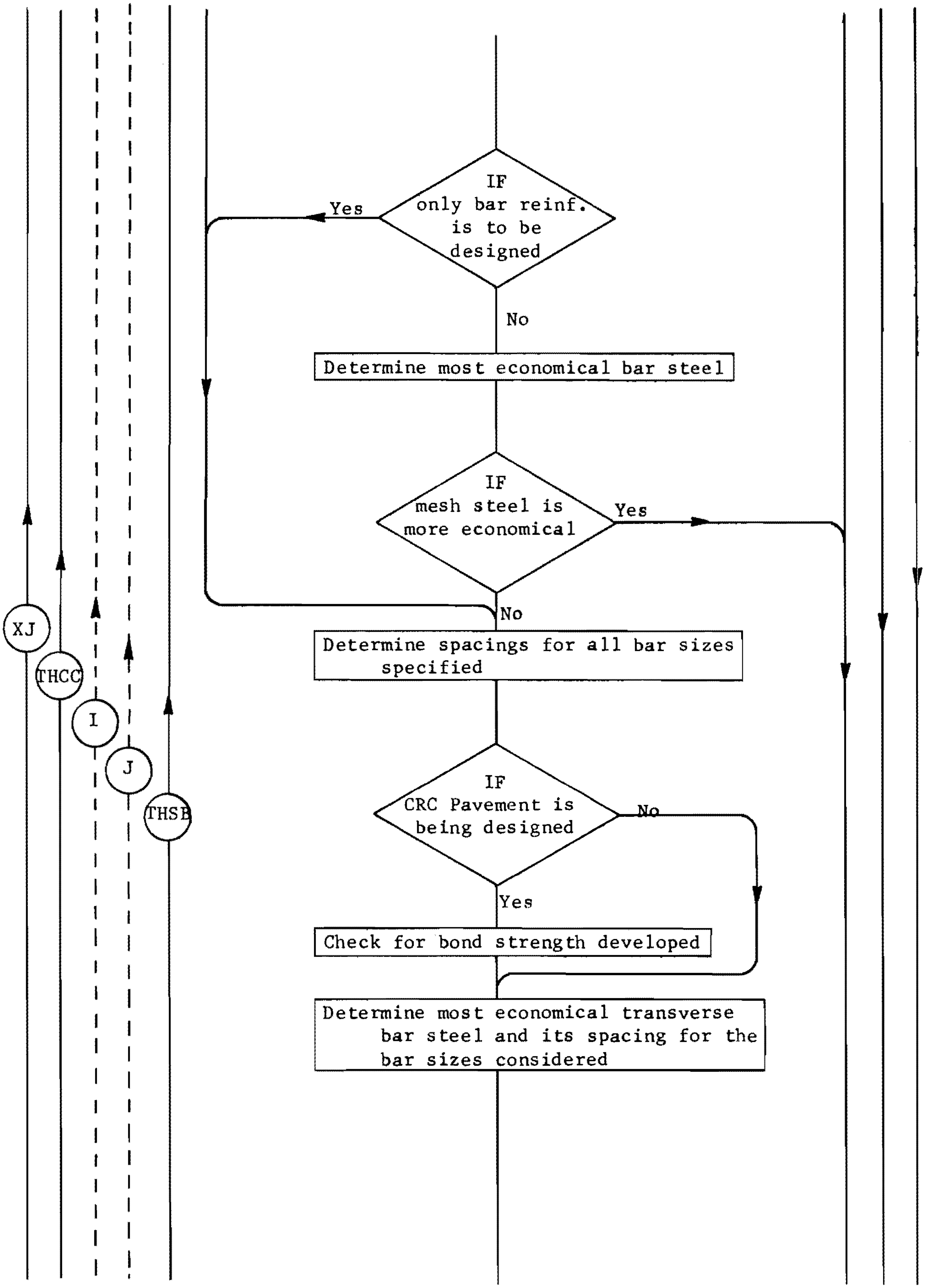

WRITE
Data for all concretes and concrete thickness
For all steel data
Determine KOUNT1 to KOUNT7 and find maximum (IKOUNT)
IF NCS3 = 2
No
WRITE Bar Reinforcement data
Yes
IF NCS3 = 1
No
WRITE Wire Mesh & Tie Bar data
Yes
IF SGK
-
o
+
Convert k value of subgrade to its E value
WRITE subgrade k data
standard deviation if > 0.0
confidence level if > 0.0
CALL subroutine PUPY to compute design value of k
Calculate subgrade E value from design k value
Calculate SGE value from Texas Triaxial value
WRITE subgrade Texas Triaxial data
its SD if > 0.0
its CL if > 0.0
Call subroutine PUPY to compute design TTC values
Calculate SGE value from design TTC value
WRITE other subgrade data

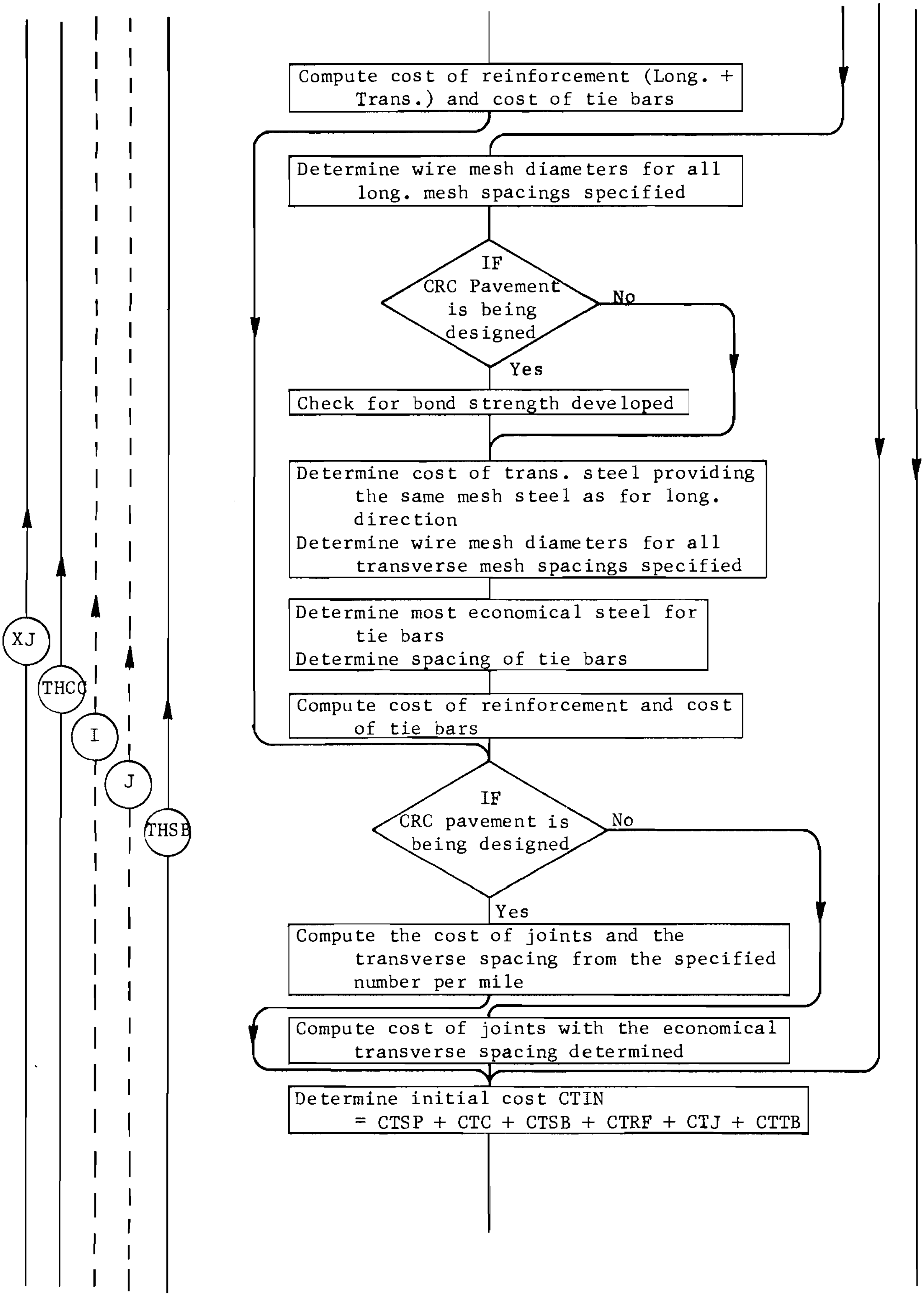

WRITE data for all subbases
IF NCS3 ≠ 1
Yes
WRITE AC overlay data
No
IF NCS3 ≠ 2
Yes
WRITE CC overlay data
No
IF NCS2 ≠ 1
Yes
WRITE seal coat data
No
WRITE Data for joints, maintenance, dimensions, and miscellaneous
Initialize storage of counters and other temporary variables
Compute cost of subgrade preparation
IF NCS1 = 2
Yes
No
Set XJ = 3.2 and Pavement identification, IDPV = 1
Set XJ = 2.2 and IDPV = 2
DO for all subbases I = 1, NSB
XJ
IF TCMIN + TSMIN(I) > TMAX
Yes
Set KTHCK = KTHCK + 1
No
Add to the previous sum the number of initial designs this subbase generates by itself
CONTINUE


Determine the number of designs generated by all the concretes by themselves
Calculate total number of initial designs possible
IF KTHCK < NSB
No
WRITE Message
STOP
Yes
XJ
THCC
DO for all subbases J = 1, NSB
IF Present Concrete THCC + TSMIN(J) ≤ TMAX
Yes
No
Continue
For THCC analyze traffic data and determine total equivalent 18 kip axles
DO for all concretes I = 1, NC
Compute cost of concrete
DO for all subbases J = 1, NSB
I
J
THSB
IF concrete + subbase thickness ≤ TMAX
No
KREJ = KREJ + 1
Yes
KSUB = KSUB + 1
Compute cost of subbase

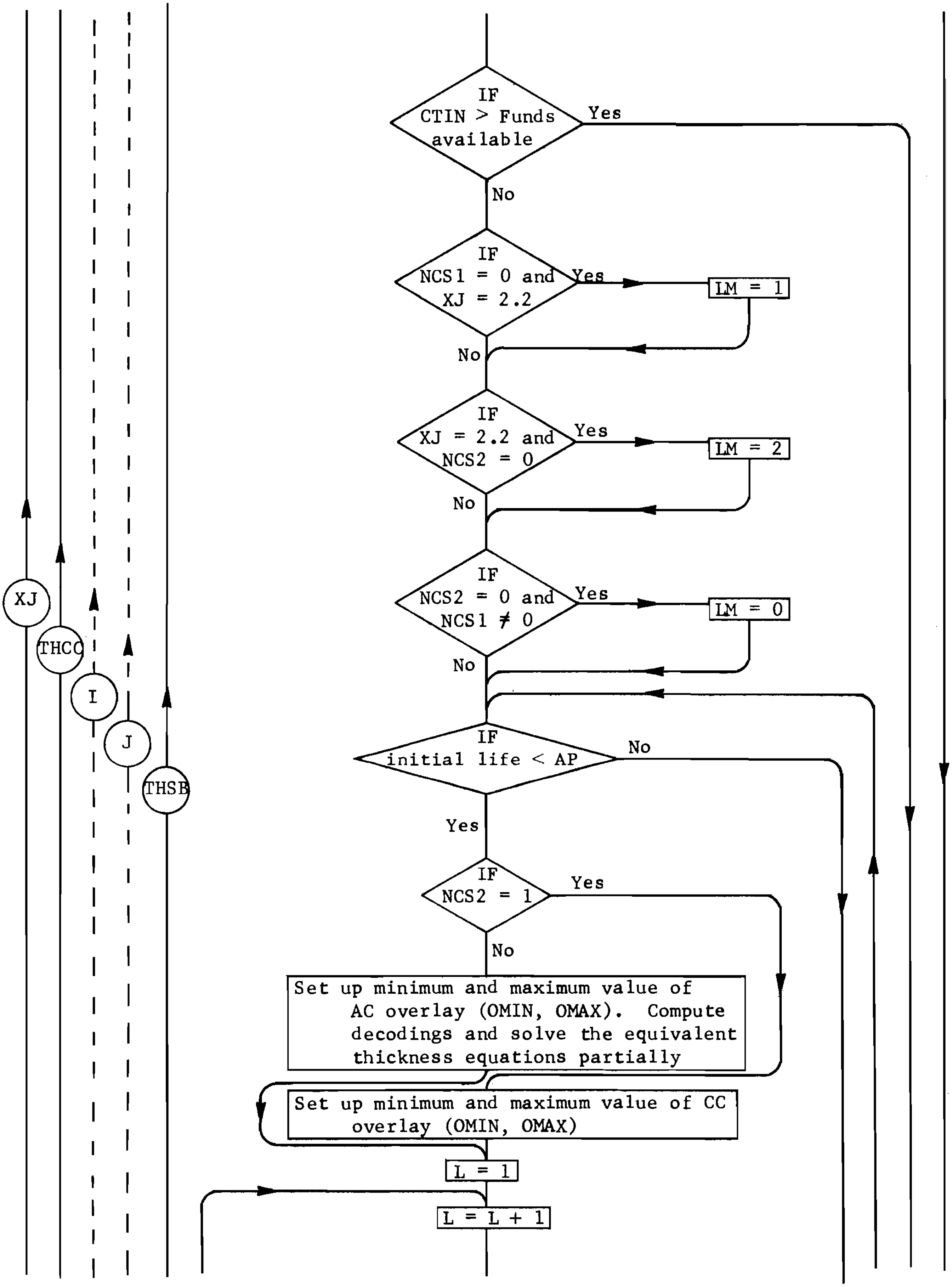

IF THSB = 0.0
Yes
No
Compute transformation decoding equations
Determine improved k value at the top of subbase using three different equations for THSB < 6.0 inches ≥ 6.0 and ≤ 12.0 inches and > 12.0 inches
Convert subgrade modulus value to k value (= TOPK)
IF Erodability Factor = 0
Yes
No
Determine reduced value of k (TOPKE) due to erodability factor
TOPKE = TOPK
IF TOPKE < 5.0
Yes
TOPKE = 5.0
No
CALL LIFE to determine life of the initial design
IF computed life ≥ min. allowed
No
KLIFE = KLIFE + 1
Yes
Call MANCE to calculate maintenance cost during the initial life (Not beyond the AP)
Reinforcement design check counter, KRCK = KRCK + 1
IF KRCK > 1
Yes
No
XJ
THCC
I
J
THSB


Determine free width of pavement according to MODEL
IF CRC Pavement is being Designed
Yes
No
IF only Mesh Reinf. is to be designed
Yes
No
Determine bar steel giving minimum sum of cost of steel and cost of Trans. joints
IF only Bar Reinf. is to be designed
Yes
No
Determine mesh steel giving minimum sum of cost of steel and cost of transverse joints
IF Mesh Steel is more Economical
No
Yes
IF only mesh reinf. is to be designed
Yes
No
Determine most economical bar steel
XJ
THCC
I
J
THSB

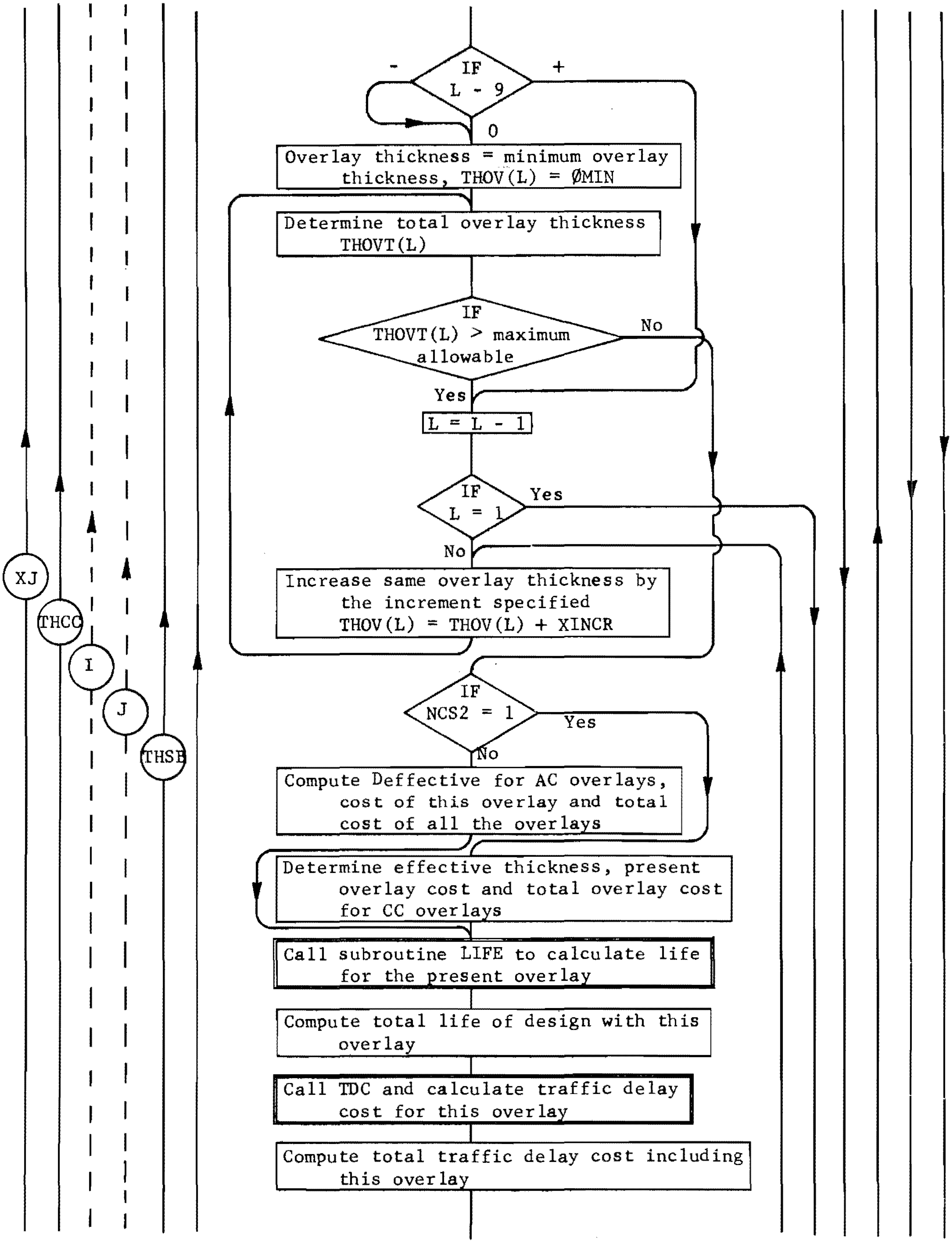

IF only bar reinf. is to be designed
Yes
No
Determine most economical bar steel
IF mesh steel is more economical
Yes
No
Determine spacings for all bar sizes specified
IF CRC Pavement is being designed
No
Yes
Check for bond strength developed
Determine most economical transverse bar steel and its spacing for the bar sizes considered
XJ
THCC
I
J
THSB



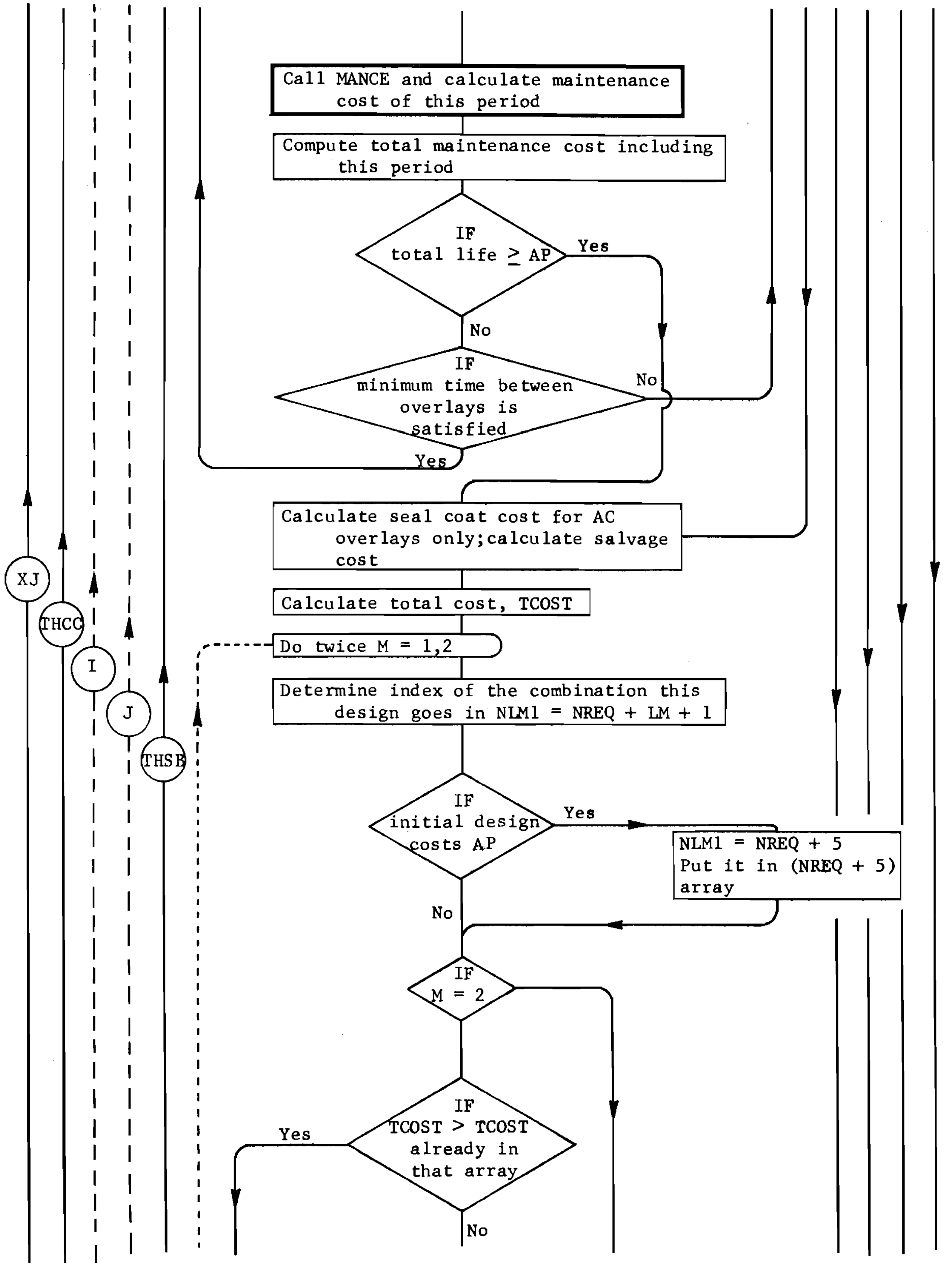
Compute cost of reinforcement (Long. + Trans.) and cost of tie bars
Determine wire mesh diameters for all long. mesh spacings specified
IF CRC Pavement is being designed
No
Yes
Check for bond strength developed
Determine cost of trans. steel providing the same mesh steel as for long. direction
Determine wire mesh diameters for all transverse mesh spacings specified
Determine most economical steel for tie bars
Determine spacing of tie bars
Compute cost of reinforcement and cost of tie bars
IF CRC pavement is being designed
No
Yes
Compute the cost of joints and the transverse spacing from the specified number per mile
Compute cost of joints with the economical transverse spacing determined
Determine initial cost CTIN = CTSP + CTC + CTSB + CTRF + CTJ + CTTB
XJ
THCC
I
J
THSB

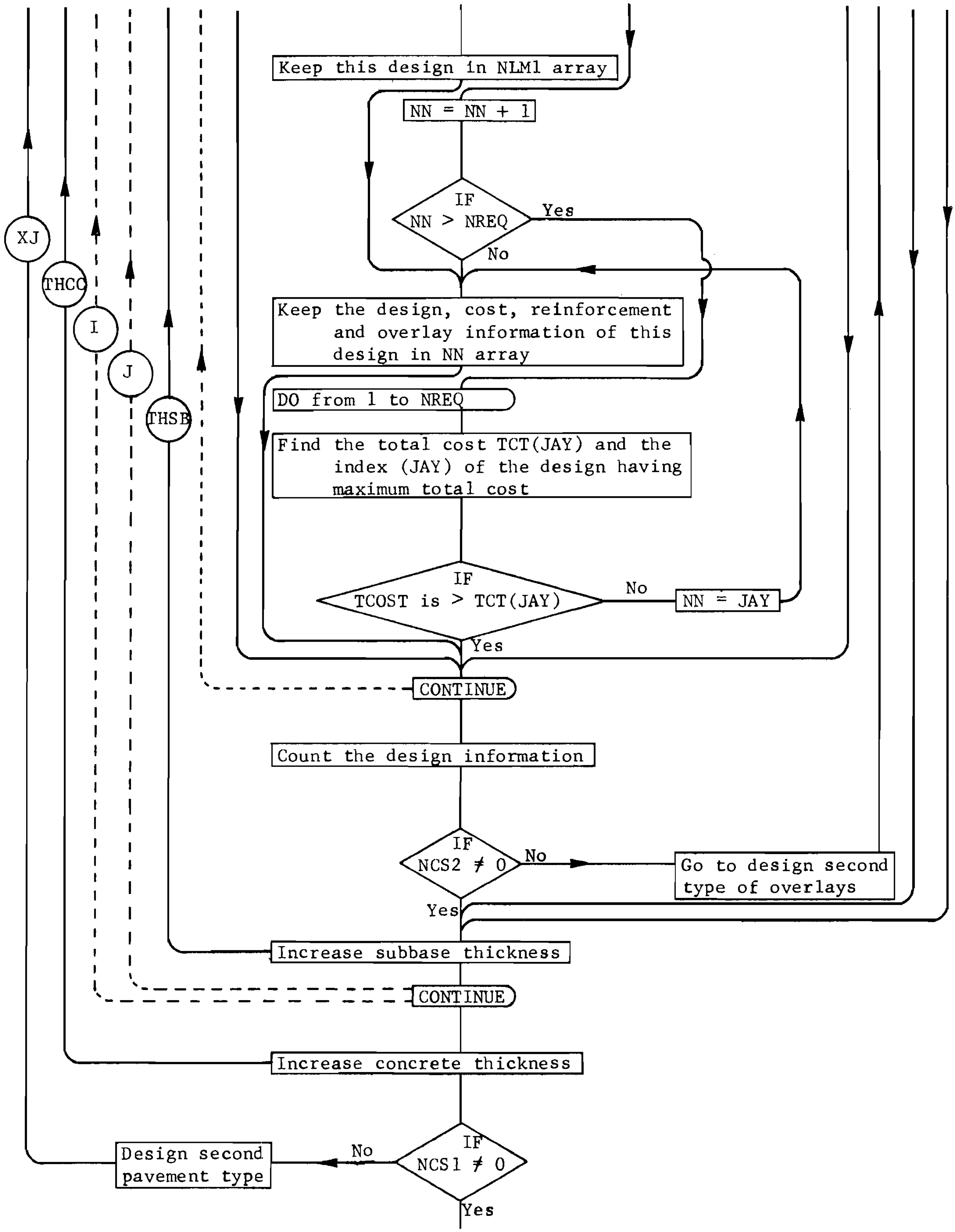


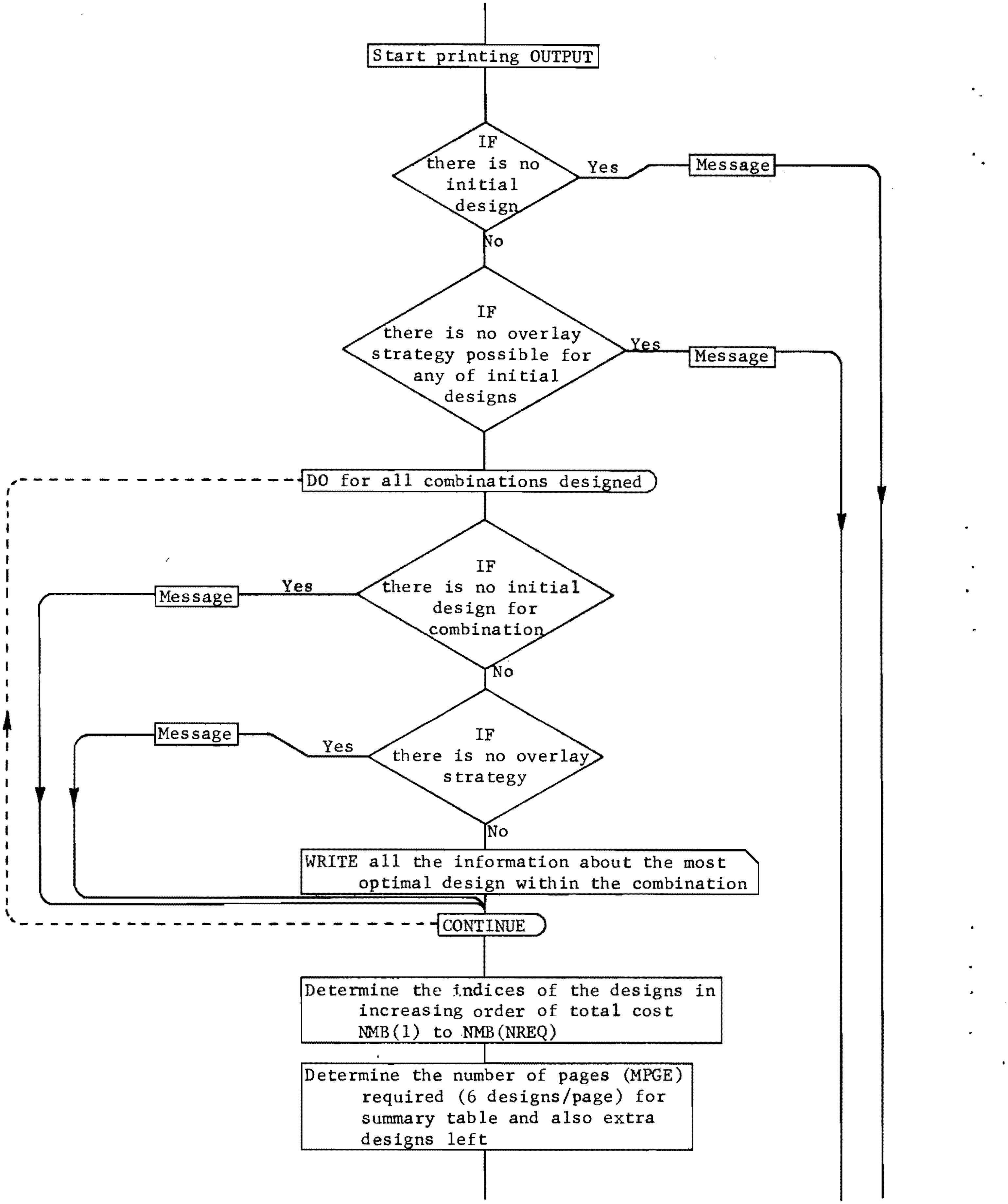
XJ
THCC
I
J
THSB
IF CTIN > Funds available
Yes
No
IF NCS1 = 0 and XJ = 2.2
Yes
LM = 1
No
IF XJ = 2.2 and NCS2 = 0
Yes
LM = 2
No
IF NCS2 = 0 and NCS1 ≠ 0
Yes
LM = 0
No
IF initial life < AP
No
Yes
IF NCS2 = 1
Yes
No
Set up minimum and maximum value of AC overlay (OMIN, OMAX). Compute decodings and solve the equivalent thickness equations partially
Set up minimum and maximum value of CC overlay (OMIN, OMAX)
L = 1
L = L + 1

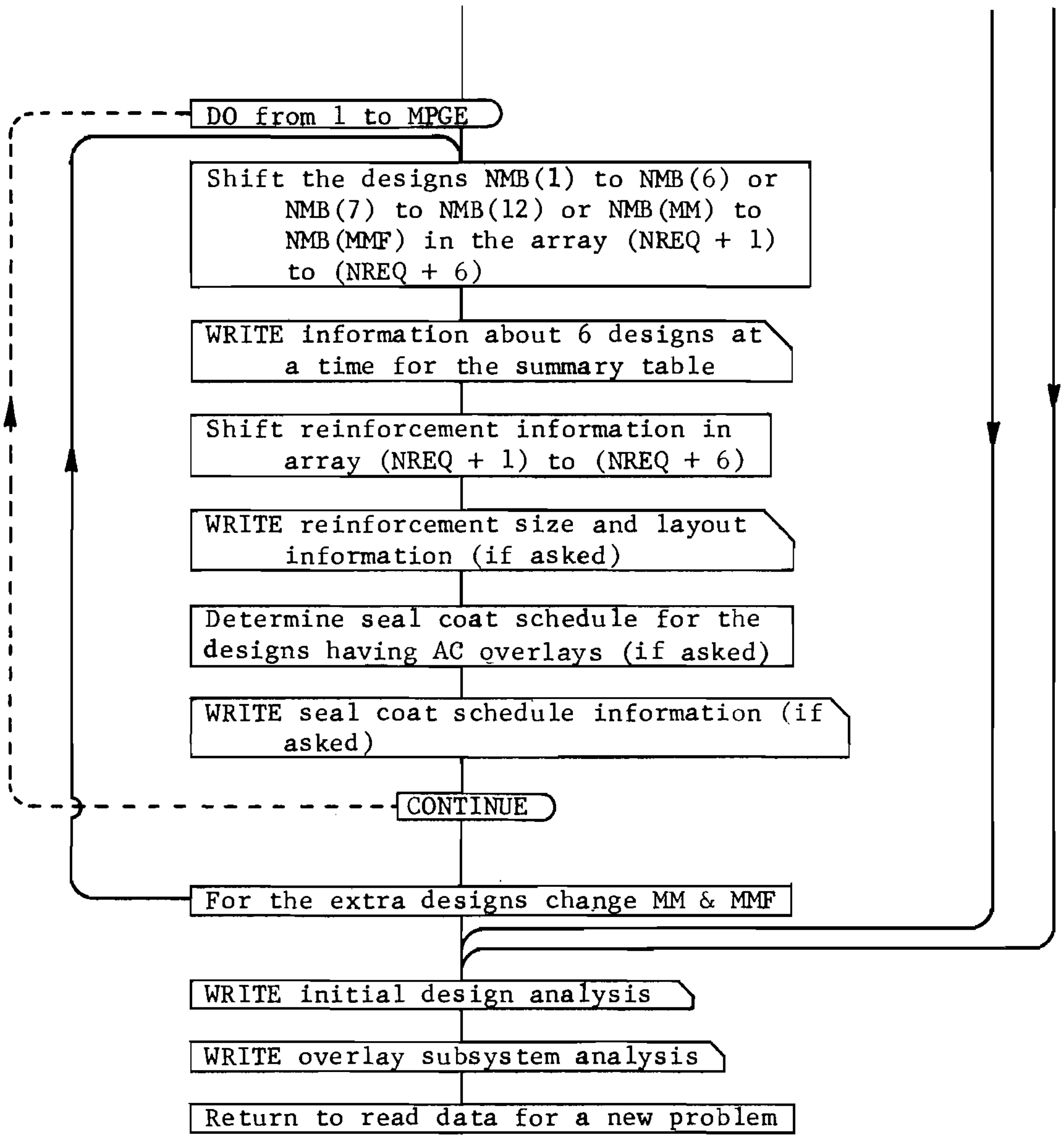


IF
L - 9
-
+
0
Overlay thickness = minimum overlay thickness, THOV(L) = ØMIN
Determine total overlay thickness THOVT(L)
IF
THOVT(L) > maximum allowable
No
Yes
L = L - 1
IF
L = 1
Yes
No
Increase same overlay thickness by the increment specified THOV(L) = THOV(L) + XINCR
IF
NCS2 = 1
Yes
No
Compute Deffective for AC overlays, cost of this overlay and total cost of all the overlays
Determine effective thickness, present overlay cost and total overlay cost for CC overlays
Call subroutine LIFE to calculate life for the present overlay
Compute total life of design with this overlay
Call TDC and calculate traffic delay cost for this overlay
Compute total traffic delay cost including this overlay
XJ
THCC
I
J
THSB

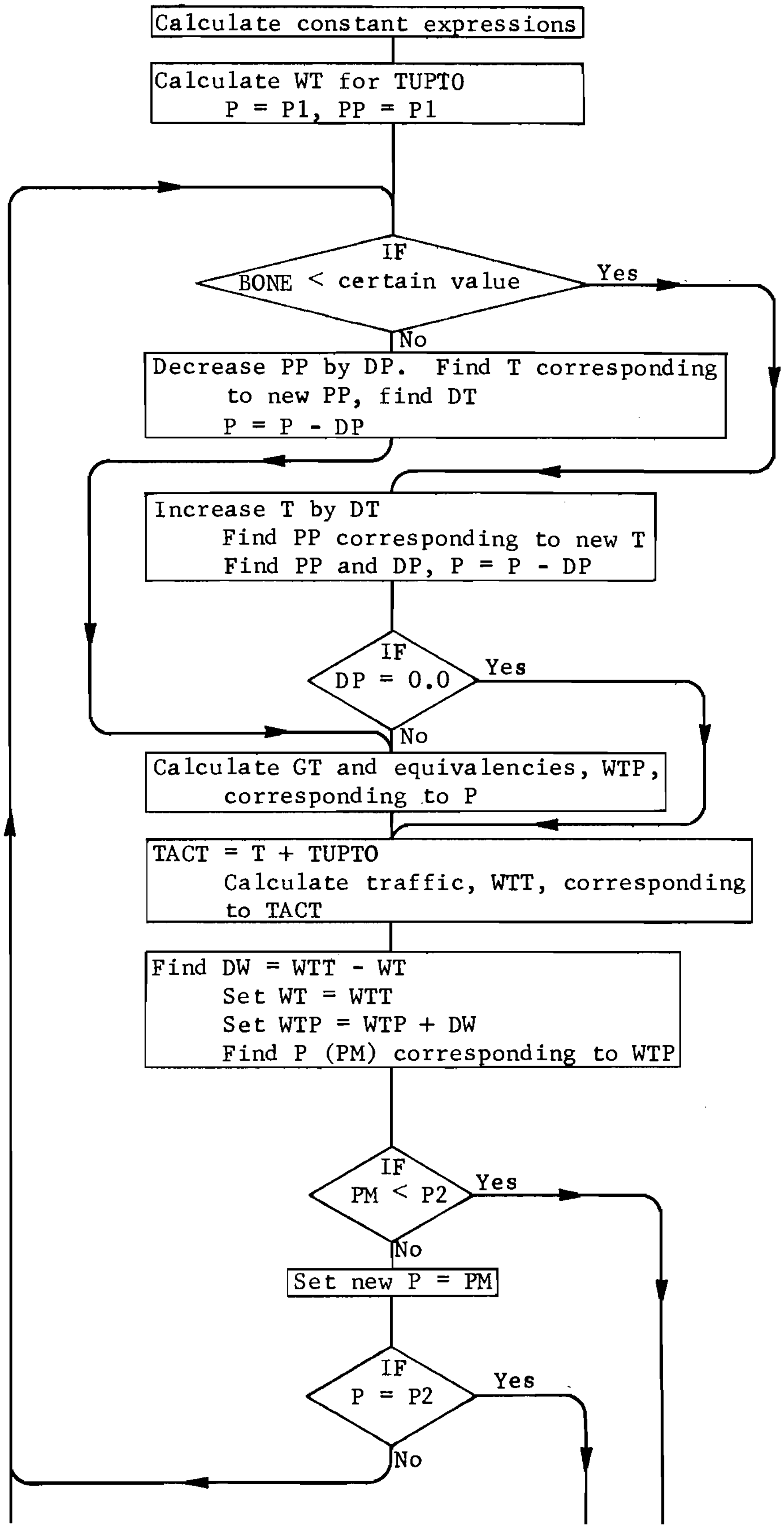

Call MANCE and calculate maintenance cost of this period
Compute total maintenance cost including this period
IF total life ≥ AP
Yes
No
IF minimum time between overlays is satisfied
No
Yes
Calculate seal coat cost for AC overlays only;calculate salvage cost
Calculate total cost, TCOST
Do twice M = 1,2
Determine index of the combination this design goes in NLM1 = NREQ + LM + 1
IF initial design costs AP
Yes
NLM1 = NREQ + 5
Put it in (NREQ + 5) array
No
IF M = 2
IF TCOST > TCOST already in that array
Yes
No
XJ
THCC
I
J
THSB

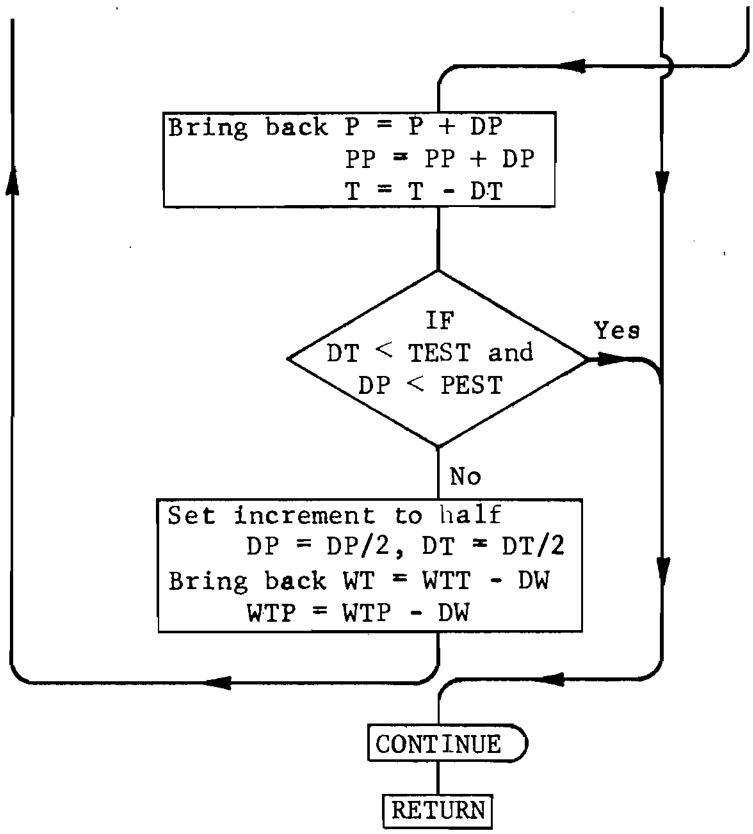

Keep this design in NLM1 array
NN = NN + 1
IF
NN > NREQ
Yes
No
XJ
THCC
I
J
THSB
Keep the design, cost, reinforcement and overlay information of this design in NN array
DO from 1 to NREQ
Find the total cost TCT(JAY) and the index (JAY) of the design having maximum total cost
IF
TCOST is > TCT(JAY)
No
NN = JAY
Yes
CONTINUE
Count the design information
IF
NCS2 ≠ 0
No
Go to design second type of overlays
Yes
Increase subbase thickness
CONTINUE
Increase concrete thickness
Design second pavement type
No
IF
NCS1 ≠ 0
Yes


Start printing OUTPUT
IF there is no initial design
Yes
Message
No
IF there is no overlay strategy possible for any of initial designs
Yes
Message
DO for all combinations designed
IF there is no initial design for combination
Yes
Message
No
IF there is no overlay strategy
Yes
Message
No
WRITE all the information about the most optimal design within the combination
CONTINUE
Determine the indices of the designs in increasing order of total cost NMB(1) to NMB(NREQ)
Determine the number of pages (MPGE) required (6 designs/page) for summary table and also extra designs left

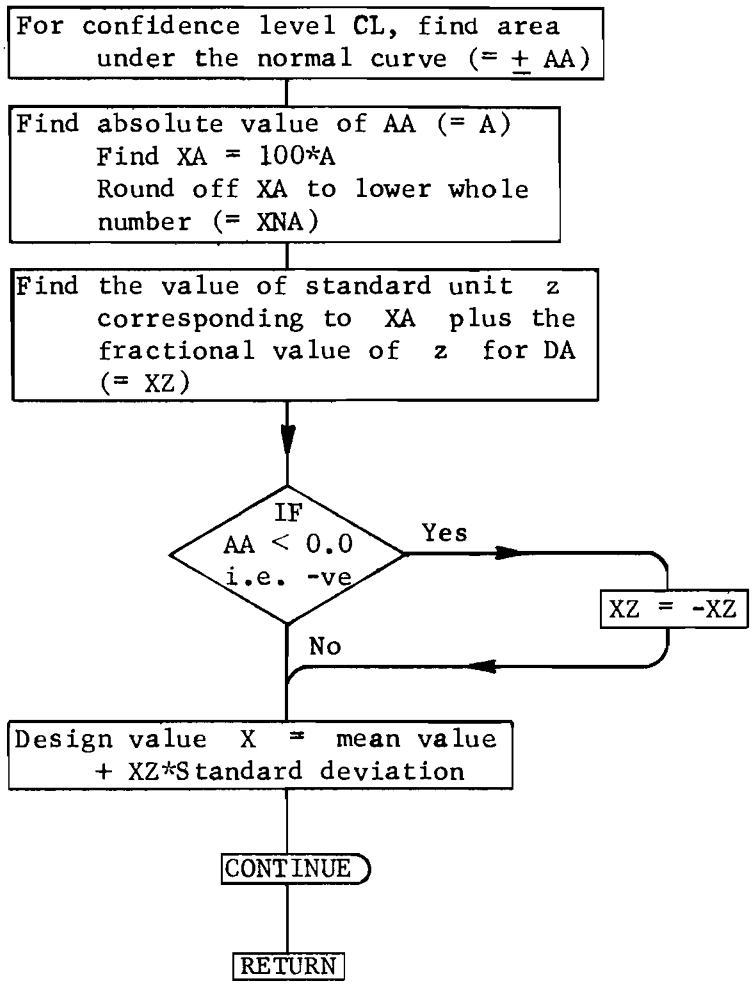

DO from 1 to MPGE
Shift the designs NMB(1) to NMB(6) or NMB(7) to NMB(12) or NMB(MM) to NMB(MMF) in the array (NREQ + 1) to (NREQ + 6)
WRITE information about 6 designs at a time for the summary table
Shift reinforcement information in array (NREQ + 1) to (NREQ + 6)
WRITE reinforcement size and layout information (if asked)
Determine seal coat schedule for the designs having AC overlays (if asked)
WRITE seal coat schedule information (if asked)
CONTINUE
For the extra designs change MM & MMF
WRITE initial design analysis
WRITE overlay subsystem analysis
Return to read data for a new problem

Subroutine LIFE

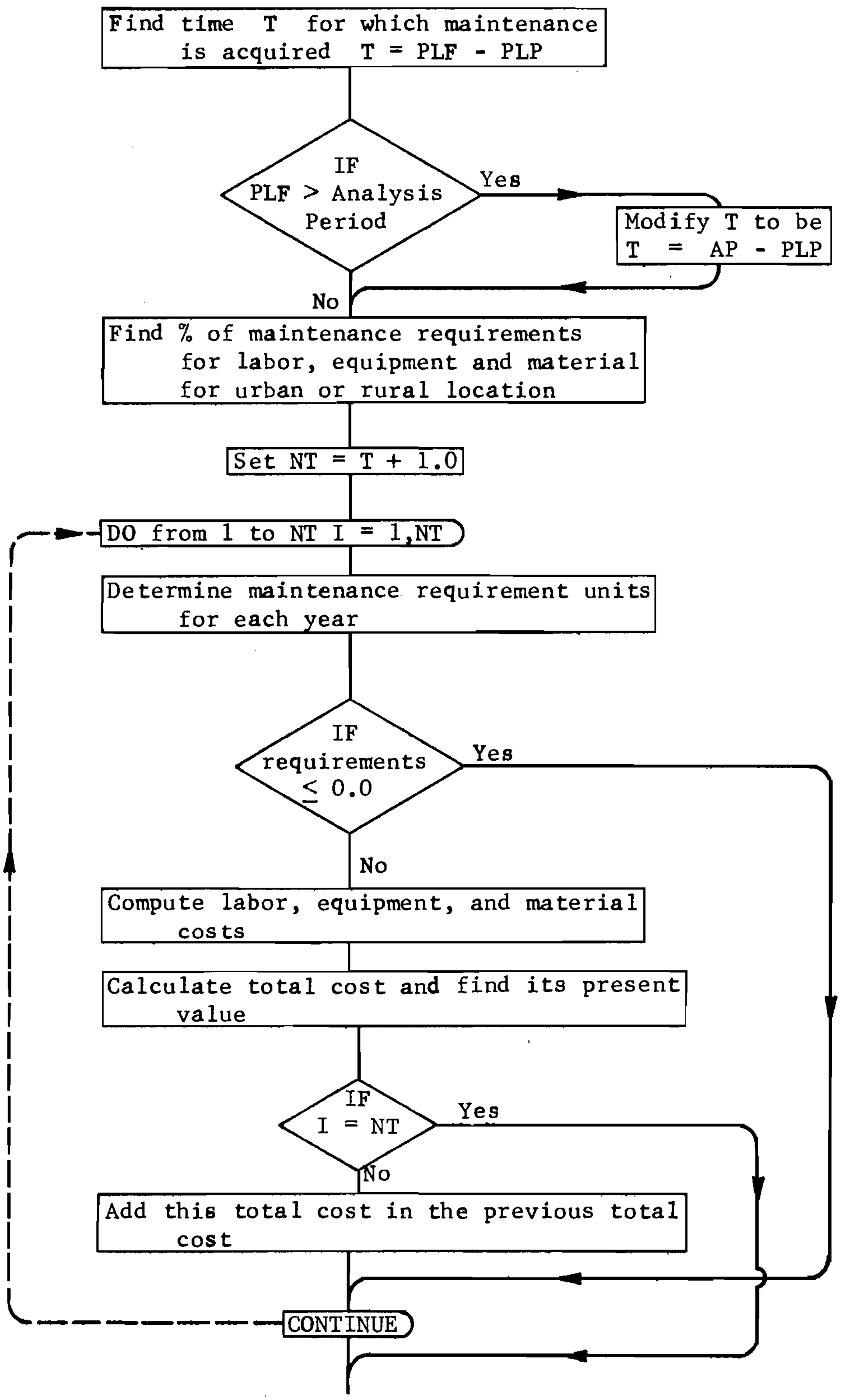


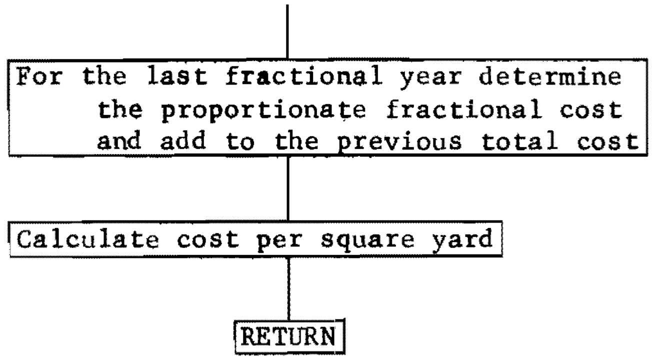

Bring back P = P + DP
PP = PP + DP
T = T - DT
IF
DT < TEST and
DP < PEST
Yes
No
Set increment to half
DP = DP/2, DT = DT/2
Bring back WT = WTT - DW
WTP = WTP - DW
CONTINUE
RETURN

Subroutine PUPY

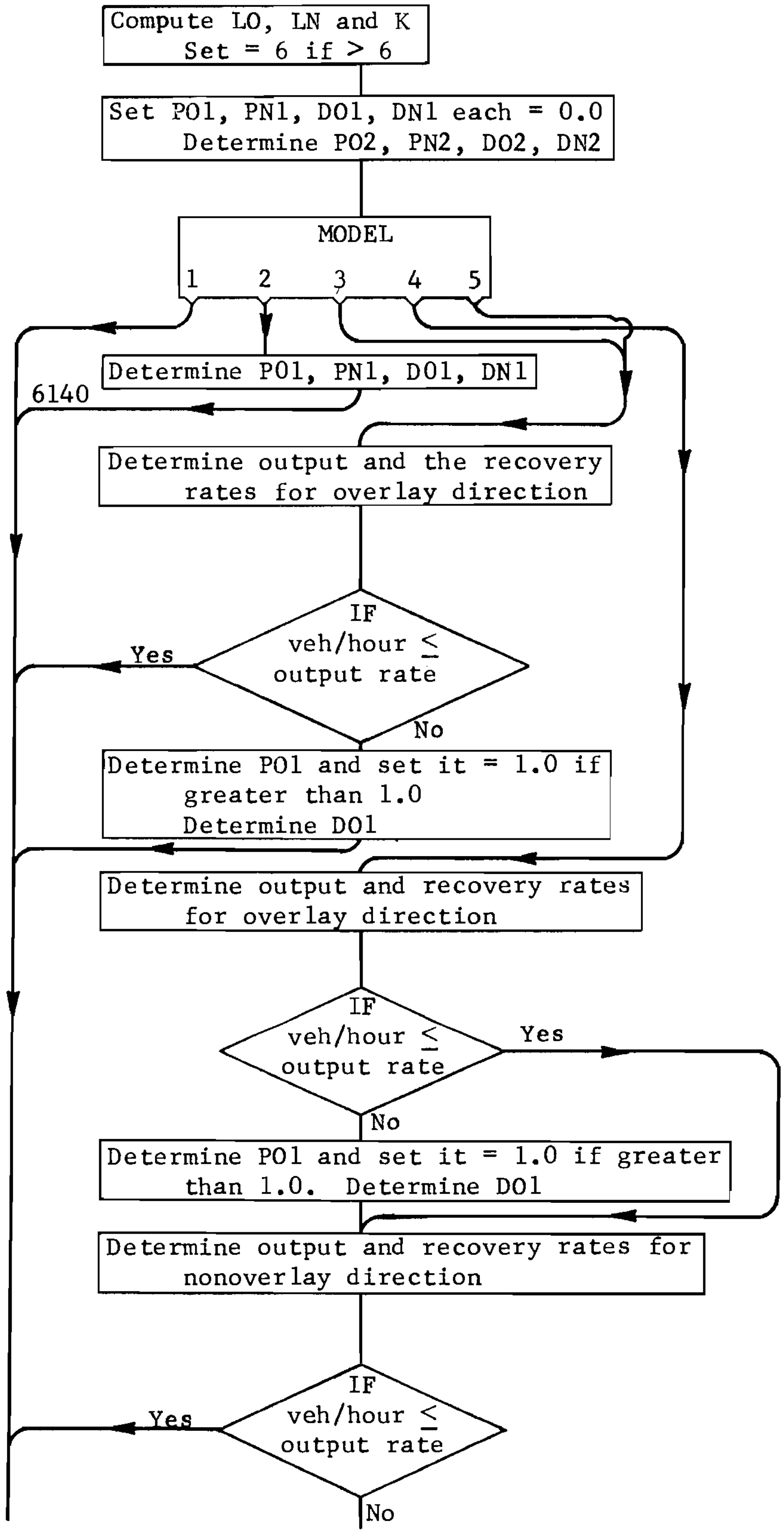


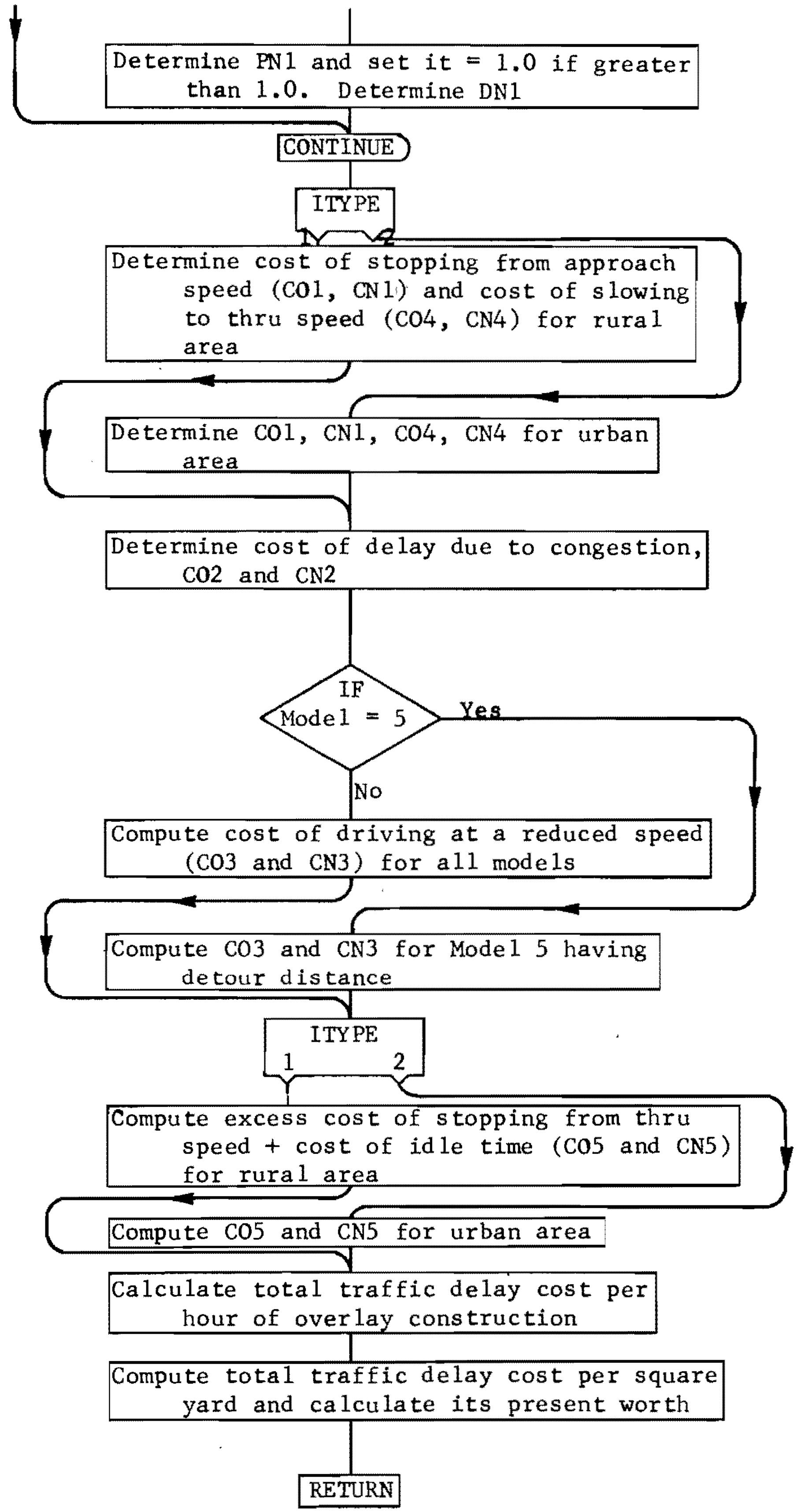
Subroutine MANCE




For the last fractional year determine the proportionate fractional cost and add to the previous total cost
Calculate cost per square yard
RETURN

Subroutine TDC





Determine PN1 and set it = 1.0 if greater than 1.0. Determine DN1
CONTINUE
ITYPE
1
2
Determine cost of stopping from approach speed (CO1, CN1) and cost of slowing to thru speed (CO4, CN4) for rural area
Determine CO1, CN1, CO4, CN4 for urban area
Determine cost of delay due to congestion, CO2 and CN2
IF Model = 5
Yes
No
Compute cost of driving at a reduced speed (CO3 and CN3) for all models
Compute CO3 and CN3 for Model 5 having detour distance
ITYPE
1
2
Compute excess cost of stopping from thru speed + cost of idle time (CO5 and CN5) for rural area
Compute CO5 and CN5 for urban area
Calculate total traffic delay cost per hour of overlay construction
Compute total traffic delay cost per square yard and calculate its present worth
RETURN

APPENDIX 3

LISTING OF PROGRAM RPS1

```
      PROGRAM RPS1 (INPUT, OUTPUT, TAPE5 = INPUT, TAPE6 = OUTPUT)
C     OCTOBER, 1970
      DIMENSION     AVGL(30),   ATBPF(4),   B(30),      BARN(4),
     1 BONY(12),    C1C(6),     C1S(4),     COD(30,2),  CODE(2,2),
     2 COMAN(11),   COSOV(11),  COTR(11),   CPCYC(6),   CPCYS(4),
     3 CPPBS(8),    CPPTS(4),   CPPWS(4),   CSC(6),     CTMAN(11),
     4 CTOVER(11),  CTTRAF(11), DIAL(4),    DIAM(4),    DIAT(4),
     5 E(6),EF(4),  EQ(30),     ES(4),      ESL(4),     FFSB(4),
     6 L1(30),      L2(30),     LFT(4),     MANT(4),    NA(30),
     7 NAME(4,3),   NAMEBS(8,3),NAMETS(4,3),NAMEWS(4,3),NCNT(4),
     8 NCODE(30),   ND(6),      NDLT(4),    NP(6),      NTDCT(4),
     9 NTHT(4),     NTMT(4),    NTOT(4),    NTOTR(4),   OVID(3),
     1 OVNAM(6),    PL(12),     PVID(2),    PVNAM(6),   RD(2,2),
     2 RNFID(2),    RNFNAM(6),  SINC(4),    SL(4),      SPAC(4),
     3 SPACL(4),    SPACT(4),   SPTIE(4),   ST(4),      SX(6),
     4 SXCL(4),     SXD(4),     SXDAT(6,2), SXDATA(2,2),SXSO(4),
     5 TBARN(4),    TCTM(11),   TCTOV(11),  TCTTD(11),  THOV(11),
     6 THOVT(11),   TITLE(15),  TS(6),      TSMAX(4),   TSMIN(4),
     7 TTCS(6),     TYSBS(8),   TYSTS(4),   TYSWS(4),   WC(6),
     8 WHO(9),      SCOT(20),   K1N(6)
C
C        RPS1  IS DIMENSIONED TO STORE A MAXIMUM OF 24 DESIGNS
C        FOR THE SUMMARY TABLE. FOR REDIMENSIONING THE PROGRAM
C        REPLACE ( 30 ) IN THE FOLLOWING CARDS BY ( 6 + IJK )
C        WHERE  IJK  IS THE MAXIMUM NUMBER OF DESIGNS TO BE STORED
      DIMENSION     CA(30),     CC(30),     CI(30),     CJ(30),
     1 CM(30),      CO(30),     CR(30),     CSB(30),    CSEAL(30),
     2 CSP(30),     CSR(30),    CT(30),     CTB(30),    IO(30),
     3 IP(30),      IR(30),     JMR(30),    JNR(30),    JPR(30),
     4 MC(30),      MLR(30),    MS(30),     MTB(30),    MTR(30),
     5 NMB(24),     NO(30),     NPP(30),    PLF(30,13), RLN(30,4),
     6 RLS(30,4),   RTN(30,4),  RTS(30,4),  STJ(30),    SUMOV(30),
     7 TBN(30,4),   TBSP(30,4), TC(30),     TCT(30),    TO(30,12),
     8 TSUB(30)
C
C
      COMMON /LIFE/ P2, P2P, XJ, TOPKE, ITER, WT
      COMMON /MANCE/ CERR, CLW, CMAT, DFTY
      COMMON /TDC/ PAPH, HPDC, PVSO, PVSN, DEQO, DEQN, AAS, ASOD,
     1      ASND,MODEL, DTSO, DTSN, DDOZ, NOLO, NOLN, ADT
C
      COMMON /ALL/ AP, ADTGR, ITYPE, RINT
C
      DATA CODE/3HSIN, 3HTAN, 3HGLE, 3HDEM /
      DATA SXDATA/3HCEN, 3H TH, 3HTER, 3HIRD /
C
      DATA (OVID(I),I=1,3)/4H AC , 4H CC , 4HNONE/
      DATA (PVID(I),I=1,2)/3HJCP,3HCRC/
      DATA (RNFID(I), I = 1, 2) /4HBARS, 4HMESH/
C
      DATA BLANK/4H,8X,/, FIL/4HF8.2/, GEO/4HF8.3/
      DATA (WHO(I),I=1,9) /3H1H+,4H,28X,6*4H,8X,,4HF8.2/
C
      DATA NOTHIN/5H      /, STAR/1H* /
C
      REAL NCODE
      REAL M1, M2, M3
      REAL K11, K22
C
C
C                   READ INPUT DATA
C
C
C                   PROBLEM DESCRIPTION
C
 1000     CONTINUE
      READ (5,1010) NPROB, TITLE
 1010 FORMAT  (A4,6X,15A4)
C
          IF (NPROB-NOTHIN) 1020,4650,1020
 1020 WRITE (6,1030) NPROB, TITLE
 1030 FORMAT  (1H1,//,5X,*I*,06X,*RIGID   PAVEMENT   SYSTEM ONE  *
     1         *RAMESH KHER         OCTOBER 1970* 19X *I-----TRIM*
     2         / 12X,*PROB *A4, 6X, 15A4 )
C
 1040 FORMAT  (1H1,   5X,*I*,06X,*RIGID   PAVEMENT   SYSTEM ONE  *
     1         *RAMESH KHER         OCTOBER 1970* 19X *I-----TRIM*
     2         / 12X,*PROB *A4, 6X, 15A4 )
C
C
C                   PROGRAM CONTROL CARD
C
      READ (5,1050) NCS1, NCS2, NCS3, PSN1, PSN4
 1050 FORMAT  (3I10, 10X, F10.0, 20X, F10.0 )
C
C        NCS     CONTROL  SWITCH  NUMBER
C
C                 SET OF SWITCHES WHICH CONTROL THE DESIGN AND
C                 OPTIMIZATION PROCESS, FOR EXAMPLE,
C
C        NCS1    DECIDES THE TYPE OF PAVEMENT TO BE DESIGNED
C                =1  FOR JCP TO BE DESIGNED ONLY
C                =2  FOR CRCP TO BE DESIGNED ONLY
C                =BLANK  FOR JCP AND CRCP BOTH TYPES OF PAVEMENTS
C                        TO BE TRIED
C        NCS2    DECIDES THE TYPE OF OVERLAYS TO BE DESIGNED
C                =1  FOR CRC OVERLAY TO BE TRIED ONLY
C                =2  FOR AC OVERLAY TO BE TRIED ONLY
C                =BLANK  FOR CRC AND AC OVERLAYS TO BE TRIED
C        NCS3    DECIDES THE TYPE OF REINFORCEMENT TO BE USED
C                =1  FOR DEFORMED BAR REINFORCEMENT ONLY
C                =2  FOR WELDED WIRE MESH REINFORCEMENT ONLY
C                =BLANK FOR DEFORMED BARS AND WIRE MESH BOTH TO BE TRIED
C
C        PSN     PRINTING  SWITCH  NUMBER
C
C                 SET OF SWITCHES WHICH DETERMINE IF SOME SPECIAL
C                 OUTPUT IS DESIRED TO BE PRINTED OUT, FOR EXAMPLE,
C                   RIGID PAVEMENT SYSTEM INPUT
C        PSN1    DECIDES WHETHER TO PRINT LONG OR SHORT FORM OF OUTPUT
C                =1  FOR SHORT FORM OF OUTPUT
C                =BLANK  FOR LONG FORM OF OUTPUT
```

```
C        PSN4    NUMBER OF DESIGNS FOR THE OUTPUT
C                BLANK - GIVES TWELVE DESIGNS ( SIX PER PAGE )
C
C
C                    TRAFFIC INPUT
C
      READ (5,1060) NL, L1(1), L2(1), NCODE(1), NA(1)
 1060 FORMAT  (3I10,F10.0,I10)
C
         IF (NL-1) 1070,1100,1090
 1070 WRITE (6,1080)
 1080 FORMAT  ( /,20X,45H*********************************************
     1          /,20X,45H*    ERROR IN INPUT DATA FOR TRAFFIC         *
     2          /,20X,45H*    NUMBER OF LOAD GROUPS OR  CARDS         *
     3          /,20X,45H*              NOT  IN  ORDER                *
     4          /,20X,45H*                                            *
     5          /,20X,45H*           PROGRAM TERMINATED               *
     6          /,20X,45H*********************************************)
         GO TO 4650
C
 1090    DO 1100 I = 2, NL
      READ (5,1060) NLCK, L1(I), L2(I), NCODE(I), NA(I)
         IF (NLCK .NE. 0) GO TO 1070
 1100    CONTINUE
C
C        NL      NUMBER OF LOAD GROUPS
C        L1-L2   RANGE OF AXLE LOADS
C        NCODE   AXLE CODE
C                1 FOR SINGLE AXLE
C                2 FOR TANDEM AXLE
C        NA      NUMBER OF AXLES IN THE RANGE, BOTH DIRECTIONS
C
C
C                    TRAFFIC GROWTH AND DISTRIBUTION
C
      READ (5,1110) AGF, ADTGR, DDF, DFL, ADT
 1110 FORMAT  (2(2F10.0,10X),F10.0)
C
C        AGF     AXLE GROWTH FACTOR (PERCENT PER YEAR)
C        ADTGR   ADT GROWTH RATE (PERCENT PER YEAR)
C        DDF     DIRECTIONAL DISTRIBUTION FACTOR (PERCENT)
C        DFL     LANE DISTRIBUTION FACTOR (PERCENT)
C        ADT     INITIAL ADT EXPECTED, ONE DIRECTION (VEH. PER DAY)
C
C
C                    USERS DECISIONS OR RESTRAINTS
C
      READ (5,1120) CMAX, TMAX, OFMIN, BOMIN, OMAXA, OMINA, OMAXC,
     1     OMINC, AP
 1120 FORMAT  (4F10.0,4F5.0,F10.0)
C
C        CMAX    MAXIMUM FUNDS AVAILABLE (DOLLARS)
C        TMAX    MAXIMUM ALLOWABLE THICKNESS, SLAB PLUS SUBBASE(INCHES)
C        BOMIN   MINIMUM TIME BETWEEN OVERLAYS (YEARS)
C        OFMIN   MINIMUM TIME TO FIRST OVERLAY (YEARS)
C        OMAXA   MAXIMUM TOTAL AC OVERLAY THICKNESS (INCHES)
C        OMINA   MINIMUM AC OVERLAY THICKNESS AT ONE TIME (INCHES)
C        OMAXC   MAXIMUM TOTAL CONCRETE OVERLAY THICKNESS (INCHES)
C        OMINC   MINIMUM CONCRETE OVERLAY THICKNESS AT ONE TIME (INCHES)
C        AP      LENGTH OF ANALYSIS PERIOD (YEARS)
C
C
C                    PERFORMANCE VARIABLES
C
      READ (5,1130) P1, P2, POV, P2P, BONE
 1130 FORMAT  (5F10.0)
C
C        P1      INITIAL SERVICEABILITY INDEX
C        P2      TERMINAL SERVICEABILITY INDEX
C        POV     SERVICEABILITY INDEX AFTER AN OVERLAY
C        P2P     LOWEST SERVICEABILITY INDEX REACHED IN INFINITE TIME
C                DUE TO SWELLING CLAY AND NO TRAFFIC
C        BONE    SWELLING CLAY PARAMETER
C
C
C                    TRAFFIC DELAY COST VARIABLES
C
      READ (5,1140) DTSO, DTSN, DDOZ, PAPH, HPDC, NOLO, NOLN, ITYPE
 1140 FORMAT  (5F10.0,2I5,10X, I10 )
      READ (5,1150) PVSO, PVSN, DEQO, DEQN, AAS, ASOD, ASND, MODEL
 1150 FORMAT  (7F10.0,I10)
C
C        DTSO    DISTANCE OVER WHICH TRAFFIC IS SLOWED,  OV.DIR.(MILES)
C        DTSN    DISTANCE OVER WHICH TRAFFIC IS SLOWED, N.OV.DIR.(MILES)
C        DDOZ    DISTANCE MEASURED ALONG DETOUR AROUND OVERLAY ZONE(MLS)
C        PAPH    PERCENT OF ADT ARRIVING EACH HOUR OF CONSTRUCTION
C        HPDC    NUMBER OF HOURS OF OVERLAY CONSTRUCTION PER DAY
C        NOLO    NO. OF OPEN LANES IN RESTRICTED ZONE,  OV. DIR.
C        NOLN    NO. OF OPEN LANES IN RESTRICTED ZONE, N.OV.DIR.
C                NOLO OR NOLN SHOULD NOT BE GREATER THAN 3
C        ITYPE   1  FOR RURAL ROAD
C                2  FOR URBAN ROAD
C
C        PVSO    VEHICLES STOPPED BY ROAD EQUIP,  OV.DIR.  (PERCENT)
C        PVSN    VEHICLES STOPPED BY ROAD EQUIP, N.OV.DIR. (PERCENT)
C        DEQO    AVG DELAY PER VEHICLE STOPPED IN RESTRICTED ZONE
C                BY ROAD EQUIPMENT AND PERSONNEL, OV. DIR.  (HOURS)
C        DEQN    AVG DELAY PER VEHICLE STOPPED IN RESTRICTED ZONE
C                BY ROAD EQUIPMENT AND PERSONNEL, NON OV. DIR. (HOURS)
C        AAS     AVG APPROACH SPEED TO OVERLAY AREA  (MPH)
C        ASOD    AVG SPEED THROUGH RESTRICTED ZONE,  OV.DIR.  (MPH)
C        ASND    AVG SPEED THROUGH RESTRICTED ZONE, N.OV.DIR. (MPH)
C        MODEL   MODEL NUMBER WHICH DESCRIBES THE TRAFFIC SITUATION
C
C
C                    MATERIALS (CONCRETES)
C
      READ (5,1160) NC, ND(1), NP(1), SX(1), SXSD(1), SXCL(1), WC(1),
     1     E(1), TS(1), CIC(1), CPCYC(1), CSC(1)
 1160 FORMAT  (I5,I3,I2,4F5.0,5F10.0)
C
         IF (NC-1) 1170,1210,1190
```

```
 1170 WRITE (6,1180)
 1180 FORMAT  ( /,20X,45H*********************************************
     1          /,20X,45H*          NO DATA ON CONCRETE              *
     2          /,20X,45H*                                           *
     3          /,20X,45H*          PROGRAM TERMINATED               *
     4          /,20X,45H*********************************************)
          GO TO 4650
C
 1190 READ (5,1200) ((ND(I), NP(I), SX(I), SXSD(I), SXCL(I), WC(I),
     1     E(I), TS(I), CIC(I), CPCYC(I), CSC(I)), I = 2, NC)
 1200 FORMAT  (5X,I3,I2,4F5.0,5F10.0)
 1210     CONTINUE
C
C         NC       NUMBER OF CONCRETE TYPES
C         ND       NO. OF DAYS AT WHICH CONC STR (SX) WAS MEASURED
C         SX       CONCRETE FLEXURAL STRENGTH, MEAN VALUE (PSI)
C         SXSD     CONCRETE FLEXURAL STRENGTH, STANDARD DEVIATION
C                  LEAVE  SXSD BLANK IF NOT KNOWN
C         SXCL     CONCRETE FLEXURAL STRENGTH, CONFIDENCE LEVEL (PER.)
C                  DO NOT LEAVE SXCL BLANK IF SXSD IS GIVEN
C         NP       1 FOR CENTER POINT LOADING FOR FLEXURAL STRENGTH TEST
C                  2 FOR THIRD POINT LOADING FOR FLEXURAL STRENGTH TEST
C         E        MODULUS OF ELASTICITY AT 28 DAYS (PSI)
C         WC       WEIGHT OF CONCRETE (POUNDS PER CUBIC FOOT)
C         TS       TENSILE STRENGTH OF CONCRETE (PSI)
C                  LEAVE TS BLANK IF NOT KNOWN
C         CIC      INITIAL COST OF EQUIP PER L.M. FOR POURING CONCRETE
C         CPCYC    COST PER CUBIC YARD OF CONCRETE
C         CSC      COST PER LANE MILE OF SURFACING CONCRETE
C                  (FOR FINISHING,CURING,AND TEXTURE)
C
C
      READ (5,1220) TCMIN, TCMAX, CINC
 1220 FORMAT  (10X,3F10.0)
C
C         TCMIN    MINIMUM ALLOWABLE CONCRETE THICKNESS (INCHES)
C         TCMAX    MAXIMUM ALLOWABLE CONCRETE THICKNESS (INCHES)
C         CINC     PRATICAL INCREMENT AT WHICH CONCRETE CAN BE
C                  EASILY POURED OR THE INCREMENT AT WHICH THE
C                  SOLUTIONS SHOULD BE MADE
C
          IF (CINC .EQ. 0.0) CINC = 1.0
C
C                       MATERIALS (SUBGRADE)
C
      READ (5,1230) SGK, SGKSD, SGKCL, TTC, TTCSD, TTCCL, FFSG,
     1     EFSG, CPLMSG
 1230 FORMAT  (6F10.0,2F5.0,F10.0)
C
C                  GIVE ONLY SGK OR TTC
C                  IF BOTH ARE GIVEN, SGK WILL BE USED
C                  LEAVE SGKSD AND/OR TTCSD BLANK IF NOT KNOWN
C                  DO NOT LEAVE SGKCL BLANK IF SGKSD IS GIVEN
C                  DO NOT LEAVE TTCCL BLANK IF TTCSD IS GIVEN
C
C         SGK      SUBGRADE K VALUE,MEAN VALUE (PCI)
C         SGKSD    SUBGRADE K VALUE,STANDARD DEVIATION
C         SGKCL    SUBGRADE K VALUE,CONFIDENCE LEVEL(PERCENT)
C         TTC      TEXAS TRIAXIAL CLASS, MEAN VALUE
C         TTCSD    TEXAS TRIAXIAL CLASS, STANDARD DEVIATION
C         TTCCL    TEXAS TRIAXIAL CLASS, CONFIDENCE LEVEL(PERCENT)
C         FFSG     FRICTION FACTOR FOR SUBGRADE
C         EFSG     ERODABILITY FACTOR FOR SUBGRADE
C         CPLMSG COST PER LANE MILE OF SUBGRADE PREPARATION
C
C
C                       MATERIALS  (SUBBASE)
C
      READ (5,1240) NSB, (NAME(1, J), J = 1, 3), EF(1), FFSB(1),
     1     TTCS(1), ES(1), CIS(1), CPCYS(1), TSMIN(1), TSMAX(1),
     2     SINC(1)
 1240 FORMAT  (I5,2A4,A2,5X,3F5.0,3F10.0,3F5.0)
C
          IF (NSB-1) 1250,1290,1270
 1250 WRITE (6,1260)
 1260 FORMAT  ( /,20X,45H*********************************************
     1          /,20X,45H*          NO DATA ON  SUBBASE              *
     2          /,20X,45H*                                           *
     3          /,20X,45H*          PROGRAM  TERMINATED              *
     4          /,20X,45H*********************************************)
          GO TO 4650
C
 1270 READ (5,1280) (((NAME(I, J), J = 1, 3), EF(I), FFSB(I), TTCS(I),
     1     ES(I), CIS(I), CPCYS(I), TSMIN(I), TSMAX(I), SINC(I)),
     2     I = 2, NSB)
 1280 FORMAT  (5X,2A4,A2,5X,3F5.0,3F10.0,3F5.0)
 1290     CONTINUE
C
C         NSB      NUMBER OF SUBBASE TYPES
C         NAME     DESCRIPTION OF SUBBASE
C         EF       ERODABILITY FACTOR FOR THE SUBBASE
C         FFSB     FRICTION FACTOR FOR SUBBASE
C         TTCS     TEXAS TRIAXIAL CLASS FOR SUBBASE
C         ES       SUBBASE MATERIAL E VALUE (PSI)
C                  GIVE ONLY TTCS OR ES. ES WILL BE USED IF BOTH ARE GIVEN
C         CIS      INITIAL COST PER L.M. OF EQUIP FOR CONSTR. OF SUBBASE
C         CPCYS    COST PER CUBIC YARD OF COMPACTED SUBBASE
C         TSMIN    MINIMUM ALLOWABLE SUBBASE THICHNESS (INCHES)
C         TSMAX    MAXIMUM ALLOWABLE SUBBASE THICKNESS (INCHES)
C         SINC     PRATICAL INCREMENTS AT WHICH SUBBASE CAN EASILY
C                  BE POURED OR THE SOLUTIONS BE MADE
C
          DO 1300 I = 1, NSB
          IF (TSMAX(I) .GT. 18.0) TSMAX(I) = 18.0
 1300     IF (SINC(I) .EQ. 0.0) SINC(I) = 3.0
C
          IF (TTCS(1) .NE. 0) IET = 1
          IF (ES(1) .NE. 0) IET = 2
          IF (IET-1) 1330,1310
C
C
C       ES VALUES WILL BE CALCULATED FOR ALL TYPES OF SUBBASES
```

```
C        FROM THEIR TTCS VALUES
 1310    DO 1320 I = 1, NSB
            ESL(I) = 4.90586-0.10744*TTCS(I)**1.5
 1320       ES(I) = 10.0**ESL(I)
C
C
C                 MATERIALS (STEEL)
C
C             MAXIMUM OF FOUR TYPES CAN BE SPECIFIED FOR EACH OF
C             1. LONGITUDINAL BAR STEEL
C             2. TRANSVERSE BAR STEEL
C             3. WIRE MESH REINFORCEMENT
C             4. TIE BAR STEEL
C
C        BARS
C
C             PROVIDE THESE TWO CARDS ONLY IF NCS3 = 0 OR = 1
C             NO CARDS IF NCS3 = 2
C
C        A. LONGITUDINAL BARS
 1330    IF (NCS3 .NE. 2) READ (5,1340) (((NAMEBS(I, J), J = 1,
     1      3), TYSBS(I), CPPBS(I)), I = 1, 4)
C
C        B. TRANSVERSE BARS
         IF (NCS3 .NE. 2) READ (5,1340) (((NAMEBS(I, J), J = 1,
     1      3), TYSBS(I), CPPBS(I)), I = 5, 8)
C
C        NAMEBS BAR STEEL IDENTIFICATION NUMBER
C        TYSBS  TENSILE YIELD POINT STRENGTH OF STEEL (PSI)
C        CPPBS  COST PER POUND OF BAR STEEL
C
C
C        MESHES
C
C             PROVIDE THIS CARD ONLY IF NCS3 = 0 OR = 2
C             NO CARD IF NCS3 = 1
C
         IF (NCS3 .NE. 1) READ (5,1340) (((NAMEWS(I, J), J = 1,
     1      3), TYSWS(I), CPPWS(I)), I = 1, 4)
C
C        NAMEWS WIRE MESH STEEL IDENTIFICATION NUMBER
C        TYSWS  TENSILE YIELD POINT STRENGTH OF STEEL (PSI)
C        CPPWS  COST PER POUND OF WIRE MESH STEEL
C
C
C        TIE BARS
C
C             PROVIDE THIS CARD ONLY IF WIRE MESHES ARE BEING USED
C             (NCS3 = 0 OR = 2).  FOR BAR REINFORCEMENT THE PROGRAM
C             USES THE SAME STEEL AS USED IN THE TRANSVERSE DIRECTION
C
         IF (NCS3 .NE. 1) READ (5,1340) (((NAMETS(I, J), J = 1,
     1      3), TYSTS(I), CPPTS(I)), I = 1, 4)
 1340 FORMAT  (4(2A4,A2,2F5.0))
C
C        NAMETS TIE BAR STEEL IDENTIFICATION NUMBER
```

```
C             TYSTS  TENSILE YIELD POINT STRENGTH OF TIE BAR STEEL (PSI)
C             CPPTS  COST PER POUND OF TIE BAR STEEL
C
C
C             BAR AND MESH SIZES TO BE TRIED
C
C
      READ (5,1350) (BARN(I), I = 1, 4), (SL(I), ST(I), I = 1, 4),
     1      TBARN
 1350 FORMAT  (16F5.0)
C
C             BARN   BAR NUMBERS TO BE TRIED
C                    NOT REQUIRED IF NCS3 = 2
C             MESHS  MESH SIZES TO BE TRIED
C                    NOT REQUIRED IF NCS3 = 1
C                    SL   IS SPACING OF LONGITUDINAL WIRES
C                    ST   IS SPACING OF TRANSVERSE WIRES
C             TBARN  TIE BAR NUMBERS TO BE TRIED
C                    NOT REQUIRED IF NCS3 = 1
C
C
C                    MATERIALS (OVERLAY)
C
C
      READ (5,1360) CIOV, CPCYAC, ACE, ACPR, CPR, COEF, CPSYR
 1360 FORMAT  ( 4F10.0,10X,3F10.0)
C
C             CIOV   INITIAL COST PER LANE MILE OF EQUIP FOR AC OVERLAYS
C             CPCYAC COST/CU YD OF IN PLACE COMPACTED ASPHALT CONCRETE
C             ACE    ASPHALT CONCRETE E VALUE
C             ACPR   PRODUCTION RATE OF COMPACTED ASPHALT CONCRETE(CU YD/HR)
C             CPR    CONCRETE PRODUCTION RATE (CUBIC YARDS PER HOUR)
C             COEF   CONCRETE COEFFICIENT FOR CORPS OF ENGINEERS FORMULA
C                    ( = 0.35 FOR BADLY CRACKED SLABS, AND,
C                      = 1.00 FOR SLABS IN EXCELLENT CONDITION )
C             CPSYR  ANY ADDITIONAL COST /SQYARD SPECIFIED BY THE USER
C
C
C                    MATERIALS (SEAL COATS)
C
             IF (NCS2 .NE. 1) READ (5,1370) TFS, TBS, CPLMS
 1370 FORMAT  (3F10.0)
C                PROVIDE THIS CARD ONLY IF NCS3 = 0 OR NCS3 = 2
C
C             TFS    TIME TO FIRST SEAL COAT AFTER AN A.C. OVERLAY
C             TBS    TIME BETWEEN SEAL COATS
C             CPLMS  COST PER LANE MILE OF A SEAL COAT
C
C
C                    JOINTS
C
      READ (5,1380) CPFTJ, CPFLJ, SLV, SUV, NJM
 1380 FORMAT  (2F10.0,10X,2F10.0,10X,I10)
C
C             CPFTJ  COST PER FOOT OF TRANS. JOINT
C             CPFLJ  COST PER FOOT OF LONG. JOINT (EXCLUDING TIE BARS)
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C
C                 GIVE THE RANGE OF SPACING BETWEEN CONTRACTION JOINTS
C                 TO BE TRIED FOR JCP
C                 NOT REQUIRED IF NCS1 = 2
C        SLV      LOWER VALUE OF SPACING
C        SUV      UPPER VALUE OF SPACING
C        NJM      NUMBER OF TRANSVERSE CONSTRUCTION OR WARPING JOINTS
C                 PER MILE PROVIDED FOR CRCP PAVEMENTS
C                 NOT REQUIRED IF NCS1 = 1
C
C
C                     MAINTENANCE,DIMENSIONS AND MISCELLANEOUS
C
      READ (5,1390) DFTY, CLW, CERR, CMAT, RINT, PSVGE, WL, NLT
 1390 FORMAT  (7F10.0,I10)
C
C        DFTY   DAYS OF FREEZING TEMPERATURE PER YEAR
C        CLW    COMPOSITE LABOR WAGE  (DOLLARS PER UNIT MAINTENANCE)
C        CERR   COMPOSITE EQUIPMENT RENTAL RATE  (DOLLARS PER
C               UNIT MAINTENANCE)
C        CMAT   COST OF MATERIALS (DOLLARS PER UNIT MAINTENANCE)
C               REFER TO MAINTENANCE MODEL IN NCHRP REPORT 42
C
C        RINT   RATE OF INTEREST OR TIME VALUE OF MONEY (PERCENT/YR)
C        PSVGE  SALVAGE PERCENT OF STRUCTURAL VALUE AT THE END OF A. P.
C
C        WL     WIDTH OF EACH LANE (FEET)
C        NLT    TOTAL NUMBER OF LANES IN BOTH DIRECTIONS
C
C
C
C                     PRINT INPUT DATA
C
C
      DO 1400 I = 1, NL
          M = NCODE(I)
          COD(I, 1) = CODE(M, 1)
          COD(I, 2) = CODE(M, 2)
          AVGL(I) = L1(I)+L2(I)
 1400     AVGL(I) = AVGL(I)/2000.
C        AVGL   AVERAGE LOAD IN KIPS
      WRITE (6,1410)
 1410 FORMAT  ( ///44X*TRAFFIC INPUT*///24X,*LOAD RANGE*,10X,*AVG. *
     1         *LOAD*,06X,*AXLE*,8X,*NO. OF AXLE* / 45X,*IN KIPS*,
     2         07X,*CODE*,08X,*APPLICATIONS* /)
      WRITE (6,1420) ((L1(I), L2(I), AVGL(I), (COD(I, J), J = 1,
     1      2), NA(I)), I = 1, NL)
 1420 FORMAT  (18X,I8,2H -,I8,7X,F8.3,7X,2A3,5X,I10)
C
C
      WRITE (6,1430) AGF, ADTGR, DDF, DFL, ADT
 1430 FORMAT  (///,35X,*TRAFFIC GROWTH AND DISTRIBUTION*///
     1         20X*AXLE GROWTH FACTOR                    *14X,F8.2/
     2         20X*ADT GROWTH RATE                       *14X,F8.2/
     3         20X*DIRECTIONAL DISTRIBUTION FACTOR       *14X,F8.2/
     4         20X*LANE DISTRIBUTION FACTOR              *14X,F8.2/
     5         20X*INITIAL AVERAGE DAILY TRAFFIC         *14X,F8.2/)
C
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,1440)
 1440 FORMAT  (// 37X,*PROGRAM CONTROLS*/,20X,*DESIGNER SPECIFIES*/)
C
                K1 = NCS1+1
          GO TO (1450,1470,1490), K1
 1450 WRITE (6,1460)
 1460 FORMAT  (30X*BOTH CRCP AND JCP PAVEMENTS TO BE TRIED*)
          GO TO 1510
 1470 WRITE (6,1480)
 1480 FORMAT  (30X*DESIGN JCP PAVEMENTS ONLY*)
          GO TO 1510
 1490 WRITE (6,1500)
 1500 FORMAT  (30X*DESIGN CRCP PAVEMENTS ONLY*)
C
 1510           K2 = NCS2+1
          GO TO (1520,1540,1560), K2
 1520 WRITE (6,1530)
 1530 FORMAT  (30X*BOTH CC AND AC OVERLAYS TO BE TRIED*)
          GO TO 1580
 1540 WRITE (6,1550)
 1550 FORMAT  (30X*PROVIDE CC OVERLAY ONLY*)
          GO TO 1580
 1560 WRITE (6,1570)
 1570 FORMAT  (30X*PROVIDE AC OVERLAY ONLY*)
C
 1580           K3 = NCS3+1
          GO TO (1590,1610,1630), K3
 1590 WRITE (6,1600)
 1600 FORMAT  (30X*BOTH DEFORMED BAR AND WIRE MESH REINFORCEMENT TO *
     1         *BE TRIED*)
          GO TO 1650
 1610 WRITE (6,1620)
 1620 FORMAT  (30X*DESIGN DEFORMED BAR REINFORCEMENT ONLY*)
          GO TO 1650
 1630 WRITE (6,1640)
 1640 FORMAT  (30X*DESIGN WELDED WIRE MESH REINFORCEMENT ONLY*)
C
 1650     IF (PSN1 .EQ. 1.) WRITE (6,1660)
 1660 FORMAT  (30X*PRINT SHORT FORM OF OUTPUT*)
          IF (PSN1 .EQ. 0.) WRITE (6,1670)
 1670 FORMAT  (30X,*PRINT LONG FORM OF OUTPUT*)
          IF (PSN4 .EQ. 0.0) PSN4 = 12.
          IF (PSN4 .GT. 24.) PSN4 = 24.
      WRITE (6,1680) PSN4
 1680 FORMAT  (30X,*PRINT FIRST* F3.0* DESIGNS IN INCREASING ORDER OF *
     1         *TOTAL COST*)
C
C
      WRITE (6,1690) CMAX, TMAX, OFMIN, BOMIN
 1690 FORMAT  (//,30X,*DESIGNERS  DECISIONS OR RESTRAINTS*//
     1         20X*MAXIMUM INITIAL FUNDS AVAILABLE (DOLLARS)*14X,F8.2/
     2         20X*MAX INITIAL THICKNESS, SLAB PLUS SUBBASE (INCHES)*
     3                                                   06X,F8.2/
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     4         20X*MIN TIME TO FIRST OVERLAY (YEARS)          *14X,F8.2/
     5         20X*MIN TIME BETWEEN OVERLAYS (YEARS)          *14X,F8.2)
         IF (NCS2 .NE. 1) WRITE (6,1700) OMAXA, OMINA
 1700 FORMAT  ( 20X*MAX TOTAL AC OVERLAY THICKNESS (INCHES)  *14X,F8.2/
     1            20X*MIN AC OVERLAY THICKNESS AT ONE TIME (INCHES)*
     2                                                         10X,F8.2)
          IF (NCS2 .NE. 2) WRITE (6,1710) OMAXC, OMINC
 1710 FORMAT  ( 20X*MAX TOTAL CONC OVERLAY THICKNESS (INCHES)*14X,F8.2/
     1            20X*MIN CONC OVERLAY THICKNESS AT ONE TIME (INCHES)*
     2                                                         08X,F8.2)
      WRITE (6,1720) AP
 1720 FORMAT  ( 20X*LENGTH OF ANALYSIS PERIOD (YEARS)        *14X,F8.2 )
C
C
      WRITE (6,1730) P1, P2, POV, P2P, BONE
 1730 FORMAT  (//,34X,*PERFORMANCE VARIABLES*//
     1         20X*INITIAL SERVICEABILITY INDEX              *14X,F8.2/
     2         20X*TERMINAL SERVICEABILITY INDEX             *14X,F8.2/
     3         20X*SERVICEABILITY INDEX AFTER AN OVERLAY     *14X,F8.2/
     4         20X*LOWER BOUND ON SERV.INDEX,NO TRAFFIC, *
     5                                      *INFINITE TIME*04X,F8.2/
     6         20X*SWELLING CLAY PARAMETER, BONE             *14X,F8.2 )
C
C
      WRITE (6,1740) DTSO, DTSN, NOLO, NOLN
      WRITE (6,1750) PVSO, PVSN, DEQO, DEQN, ASOD, ASND, AAS
      WRITE (6,1760) DDOZ, PAPH, HPDC, MODEL
 1740 FORMAT  (//,31X,*TRAFFIC DELAY COST VARIABLES* //  20X
     1         *DISTANCE OVER WHICH TRAFFIC IS SLOWED,   OV.DIRECTION*
     2         02X,F8.2 / 59X, *N.OV.DIRECTION*,2X,F8.2 / 20X
     3         *NO. OF OPEN LANES IN RESTRICTED ZONE,    OV.DIRECTION*
     4         02X,  I8 / 59X, *N.OV.DIRECTION*,2X,I8  )
 1750 FORMAT  (20X*PERCENT VEHICLES STOPPED BY ROAD EQUIP,  OV.*
     1         *DIRECTION*  02X,F8.2 / 59X,*N.OV.DIRECTION*,2X,F8.2/  20X
     2         *AVG DELAY CAUSED BY ROAD EQUIP (HOURS),  OV.DIRECTION*
     3         02X,F8.2 / 59X,*N.OV.DIRECTION*,2X,F8.2/  20X
     4         *AVG SPEED THROUGH OVERLAY ZONE (MPH),    OV.DIRECTION*
     5         02X,F8.2 / 59X,*N.OV.DIRECTION*,2X,F8.2/  20X
     6         *AVERAGE APPROACH SPEED TO OVERLAY AREA* 17X,F8.2 )
 1760 FORMAT  (20X*DETOUR DISTANCE AROUND OVERLAY ZONE          *
     1         12X,F8.2 / 20X        *ADT ARRIVING EACH HOUR OF *
     2         *CONSTRUCTION              * 07X,F8.2 / 20X   *NO. OF *
     3         *HOURS/DAY OVERLAY CONSTRUCTION OCCURS* 11X,F8.2 /
     4         20X*TRAFFIC MODEL USED IN THE ANALYSIS* 21X,I8 /
     5         20X*ROAD LOCATION* )
          IF (ITYPE .EQ. 1) WRITE (6,1770)
          IF (ITYPE .EQ. 2) WRITE (6,1780)
 1770 FORMAT  (1H+, 77X, *RURAL*)
 1780 FORMAT  (1H+, 77X, *URBAN*)
C
C
C                    MATERIALS
C
      WRITE (6,1030) NPROB, TITLE
C
          DO 1790 I = 1, NC
          IF (NP(I) .EQ. 0) NP(I) = 2
          IF (ND(I) .EQ. 0) ND(I) = 28
      CALL PUPY (SX(I), SXSD(I), SXCL(I), SXD(I))
          IF (ND(I) .EQ. 7) SXD(I) = 1.23*SXD(I)
          IF (NP(I) .EQ. 1) SXD(I) = 0.90*SXD(I)
          IF (TS(I) .LE. 0.0) TS(I) = 0.40*SXD(I)
               ISX = NP(I)
               SXDAT(I, 1) = SXDATA(ISX, 1)
 1790          SXDAT(I, 2) = SXDATA(ISX, 2)
      WRITE (6,1800) (I, I = 1, NC)
 1800 FORMAT  (/// 35X,*MATERIALS (CONCRETE)*//
     1           12X,*CONCRETE MIX DESIGN NUMBER  *7X,6(I5,5X))
      WRITE (6,1810) (ND(I), I = 1, NC)
 1810 FORMAT  (12X,*AGE OF TESTING CONCRETE      *7X,6(I5,5X))
      WRITE (6,1820) ((SXDAT(I, J), J = 1, 2), I = 1, NC)
 1820 FORMAT  (12X,*MEASURING POINT                *6X,6(2A3,4X))
      WRITE (6,1830) (SX(I), I = 1, NC)
 1830 FORMAT  (12X,*FLEXURAL STRENGTH,MEAN VALUE*2X,6F10.2)
      WRITE (6,1840) (SXSD(I), I = 1, NC)
 1840 FORMAT  (12X,*FLEXURAL STRENGTH,STD. DEV. *2X,6F10.2)
      WRITE (6,1850) (SXCL(I), I = 1, NC)
 1850 FORMAT  (12X,*FLEX.STR.DESIGN CONF.LEVEL  *2X,6F10.2)
      WRITE (6,1860) (TS(I), I = 1, NC)
 1860 FORMAT  (12X,*TENSILE STRENGTH             *2X,6F10.2)
      WRITE (6,1870) (E(I), I = 1, NC)
 1870 FORMAT  (12X,*ELASTIC MODULUS              *2X,6F10.0)
      WRITE (6,1880) (WC(I), I = 1, NC)
 1880 FORMAT  (12X,*WEIGHT                       *2X,6F10.2)
      WRITE (6,1890) (CIC(I), I = 1, NC)
 1890 FORMAT  (12X,*CONSTRUCTION EQUIPMENT COST *2X,6F10.2)
      WRITE (6,1900) (CPCYC(I), I = 1, NC)
 1900 FORMAT  (12X,*COST PER CUBIC YARD          *2X,6F10.2)
      WRITE (6,1910) (CSC(I), I = 1, NC)
 1910 FORMAT  (12X,*COST OF SURFACING CONCRETE  *2X,6F10.2)
C
C
      WRITE (6,1920) TCMIN, TCMAX, CINC
 1920 FORMAT  (//20X*MINIMUM ALLOWABLE CONCRETE THICKNESS* 08X,
     1         F8.2,/20X*MAXIMUM ALLOWABLE CONCRETE THICKNESS*
     2          08X,F8.2,/20X*PRACTICAL INCREMENT FOR POURING *
     3           *CONCRETE* 04X,F8.2)
C
               KOUNT1 = 0
               KOUNT2 = 0
               KOUNT3 = 0
               KOUNT4 = 0
               KOUNT5 = 0
               KOUNT6 = 0
               KOUNT7 = 0
C
          DO 1930 I = 1, 4
          IF (TYSBS(I) .NE. 0.) KOUNT1 = KOUNT1+1
               J = I+4
          IF (TYSBS(J) .NE. 0.) KOUNT2 = KOUNT2+1
          IF (TYSWS(I) .NE. 0.) KOUNT3 = KOUNT3+1
          IF (SL(I) .NE. 0.) KOUNT4 = KOUNT4+1
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      IF (TYSTS(I) .NE. 0.) KOUNT5 = KOUNT5+1
      IF (BARN(I) .NE. 0.) KOUNT6 = KOUNT6+1
      IF (TBARN(I) .NE. 0.) KOUNT7 = KOUNT7+1
 1930 CONTINUE
C
         IKOUNT = MAX0(KOUNT1, KOUNT2, KOUNT3, KOUNT5)
         KOUNT2 = KOUNT2+4
C
      WRITE (6,1940) (I, I = 1, IKOUNT)
 1940 FORMAT (//,36X,*MATERIALS (STEEL)*//38X,4(10X,I2))
      IF (NCS3 .EQ. 2) GO TO 1990
      WRITE (6,1950) ((NAMEBS(I, J), J = 1, 3), I = 1, KOUNT1)
      WRITE (6,1960) (TYSBS(I), I = 1, KOUNT1)
      WRITE (6,1970) (CPPBS(I), I = 1, KOUNT1)
      WRITE (6,1980) ((NAMEBS(I, J), J = 1, 3), I = 5, KOUNT2)
      WRITE (6,1960) (TYSBS(I), I = 5, KOUNT2)
      WRITE (6,1970) (CPPBS(I), I = 5, KOUNT2)
      WRITE (6,1975) (BARN(I), I = 1, KOUNT6)
 1950 FORMAT (12X,*BARS* / 16X,*LONGITUDINAL*/
     1      18X*BAR STEEL ASTM DESIG* 4(2X,2A4, A2 ))
 1960 FORMAT (18X*TENSILE YIELD PT STR*  4(2X,F10.2))
 1970 FORMAT (18X*COST/LB OF BAR STEEL*  4(2X,F10.3))
 1975 FORMAT (16X*BAR NOS, TO BE TRIED  *4(2X,F10.0))
 1980 FORMAT (16X*TRANSVERSE*/
     1       18X*BAR STEEL ASTM DESIG* 4(2X,2A4, A2 ))
C
 1990 IF (NCS3 .EQ. 1) GO TO 2070
      WRITE (6,2000) ((NAMEWS(I, J), J = 1, 3), I = 1, KOUNT3)
      WRITE (6,1960) (TYSWS(I), I = 1, KOUNT3)
      WRITE (6,2010) (CPPWS(I), I = 1, KOUNT3)
      WRITE (6,2020) (SL(I), I = 1, KOUNT4)
      WRITE (6,2030) (ST(I), I = 1, KOUNT4)
 2000 FORMAT (/12X*WIRE MESHES* /
     1        18X*WIRE MESH ASTM DESIG*  4(2X,2A4, A2 ))
 2010 FORMAT (18X*COST/LB OF WIRE MESH*  4(2X,F10.3))
 2020 FORMAT (16X*MESH SIZES TO BE TRIED*/
     1       17X*LONG. WIRE SPACING  *  4(2X,F10.2))
 2030 FORMAT (17X*TRAN. WIRE SPACING  *  4(2X,F10.2))
C
      WRITE (6,2040) ((NAMETS(I, J), J = 1, 3), I = 1, KOUNT5)
      WRITE (6,1960) (TYSTS(I), I = 1, KOUNT5)
      WRITE (6,2050) (CPPTS(I), I = 1, KOUNT5)
      WRITE (6,2060) (TBARN(I), I = 1, KOUNT7)
 2040 FORMAT (/12X*TIE BARS USED WITH W. MESH * /
     1       18X*TIE BAR ASTM  DESIG.*  4(2X,2A4, A2 ))
 2050 FORMAT (18X*COST /LB OF TIE BARS*  4(2X,F10.3))
 2060 FORMAT (16X*TIE BAR NOS TO BE TRIED *4(F10.0,2X))
 2070 CONTINUE
C
      WRITE (6,1040) NPROB, TITLE
C
         ITEST = 0
      IF (SGK-ITEST) 2080,2140,2080
C     MODULUS VALUE (SGE) FOR SUBGRADE WILL BE CALCULATED FROM SGK
 2080    SGE = 23.925*SGK
C
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```
      WRITE (6,2090) SGK
 2090 FORMAT  (//35X*MATERIALS (SUBGRADE)*//20X*SUBGRADE*
     1          * K MEAN VALUE* 34X,F8.2)
C
         IF (SGKSD-ITEST) 2100,2200,2100
 2100 WRITE (6,2110) SGKSD
 2110 FORMAT  (20X,*SUBGRADE K VALUE, STANDARD DEVIATION* 19X,F8.2)
C
         IF (SGKCL-ITEST) 2120,2200,2120
 2120 WRITE (6,2130) SGKCL
 2130 FORMAT  (20X,*SUBGRADE K VALUE, DESIGN CONFIDENCE LEVEL*
     1          14X,F8.2)
C
C       CALL PUPY TO CALCULATE SGKD
      CALL PUPY (SGK, SGKSD, SGKCL, SGKD)
C
            SGE = 23.925*SGKD
         GO TO 2200
C       MODULUS VALUE (SGE) FOR SUBGRADE WILL BE CALCULATED FROM TTC
C
 2140       SGEL = 4.90586-0.10744*TTC**1.5
            SGE = 10.0**SGEL
C
      WRITE (6,2150) TTC
 2150 FORMAT  (///46X*SUBGRADE*///20X*TEXAS TRIAXIAL CLASS, MEAN VALUE*
     1          23X,F8.2)
C
         IF (TTCSD-ITEST) 2160,2200,2160
 2160 WRITE (6,2170) TTCSD
 2170 FORMAT  (20X,*SUBG. TEXAS TRIAXIAL CLASS,STD. DEVIATION*,9X,F8.2)
C
         IF (TTCCL-ITEST) 2180,2200,2180
 2180 WRITE (6,2190) TTCCL
 2190 FORMAT  (20X,*SUBG. TEXAS TRIAXIAL CL. CONFIDENCE LEVEL*10X,F8.2)
C
C       CALL PUPY TO CALCULATE TTCD
      CALL PUPY (TTC, TTCSD, TTCCL, TTCD)
C
            SGEL = 4.90586-0.10744*TTCD**1.5
            SGE = 10.0**SGEL
C
 2200 WRITE (6,2210) FFSG, EFSG, CPLMSG
 2210 FORMAT  ( ,20X,*SUBGRADE FRICTION FACTOR*,31X,F8.2,
     1          /,20X,*SUBGRADE ERODABILITY FACTOR*,28X,F8.2,
     2          /,20X,*COST PER LANE MILE OF SUBGRADE PREPARATION*,
     3            13X, F8.2 )
C
      WRITE (6,2220) ((NAME(I, J), J = 1, 3), I = 1, NSB)
 2220 FORMAT  ( // 35X,*MATERIALS (SUBBASE) * // 20X
     1         *SUBBASE TYPE           *  4(2A4,A2))
      WRITE (6,2230) (EF(I), I = 1, NSB)
 2230 FORMAT  ( 20X*ERODABILITY FACTOR    * 4F10.2 )
      WRITE (6,2240) (FFSB(I), I = 1, NSB)
 2240 FORMAT  ( 20X*FRICTION FACTOR       * 4F10.2 )
         IF (IET .EQ. 1) WRITE (6,2250) (TTCS(I), I = 1, NSB)
 2250 FORMAT  ( 20X*TEXAS TRIAXIAL CLASS  * 4F10.2 )
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      IF (IET .EQ. 2) WRITE (6,2260) (ES(I), I = 1, NSB)
 2260 FORMAT  ( 20X*ELASTIC MODULUS        * 4F10.0 )
      WRITE (6,2270) (CIS(I), I = 1, NSB)
 2270 FORMAT  ( 20X*CONSTR EQUIPMENT COST * 4F10.2 )
      WRITE (6,2280) (CPCYS(I), I = 1, NSB)
 2280 FORMAT  ( 20X*COST/ COMPACTED CU YD * 4F10.2 )
      WRITE (6,2290) (TSMIN(I), I = 1, NSB)
 2290 FORMAT  ( 20X*MIN ALLOWED THICKNESS * 4F10.2 )
      WRITE (6,2300) (TSMAX(I), I = 1, NSB)
 2300 FORMAT  ( 20X*MAX ALLOWED THICKNESS * 4F10.2 )
      WRITE (6,2310) (SINC(I), I = 1, NSB)
 2310 FORMAT  ( 20X*INCREMENT FOR SUBBASE * 4F10.2 )
C
      WRITE (6,2320) CIOV
 2320 FORMAT  (//,46X*OVERLAY* //
     1        20X*INITIAL COST PER LANE MILE OF EQUIPMENT FOR*
     2                                * AC OVERLAYS* 0X,F7.2)
      IF (NCS2 .NE. 1) WRITE (6,2330) CPCYAC, ACE, ACPR
 2330 FORMAT  ( 20X*COST/CU YD OF IN PLACE COMPACTED ASPHALT CONCRETE*
     1                                                    06X,F8.2/
     2          20X*ASPHALT CONCRETE MODULUS VALUE          *13X,F8.0/
     3          20X*PRODUCTION RATE OF COMPACTED ASPHALT CONCRETE*
     4                                                    10X,F8.2)
      IF (NCS2 .NE. 2) WRITE (6,2340) CPR, COEF
 2340 FORMAT  ( 20X*CONCRETE PRODUCTION RATE                *13X,F8.2/
     1          20X*CONCRETE COEFFICIENT                    *13X,F8.2)
      IF (CPSYR .NE. 0.0) WRITE (6,2350) CPSYR
 2350 FORMAT  (20X*RANDOM ADDITIONAL COST/SQ YD FOR ANYTHING *13X,F8.2)
C
      IF (NCS2 .NE. 1) WRITE (6,2360) TFS, TBS, CPLMS
 2360 FORMAT  (/ ,45X,*SEAL COATS* //
     1        20X*TIME TO FIRST SEAL COAT AFTER AC OVERLAY *14X,F8.2/
     2        20X*TIME BETWEEN SEAL COATS                  *14X,F8.2/
     3        20X*COST PER LANE MILE OF A SEAL COAT        *14X,F8.2)
C
      WRITE (6,2370) CPFTJ, CPFLJ, SLV, SUV
 2370 FORMAT  (/ ,47X,*JOINTS* //
     1        20X*COST/FT OF TRANS. JOINT (SAWING, DOWELS AND*
     2                                   */OR SEALING)*00X,F7.2/
     3        20X*COST/FT OF LONG. JOINT (SEALING)*        23X,F8.2 /
     4        20X*RANGE OF SPACING FOR CONTRACTION JOINTS, *
     5        *LOWER VALUE* 3X,F8.2 /  61X,
     6          *UPPER VALUE* 3X, F8.2)
      IF (NCS1 .NE. 1) WRITE (6,2380) NJM
 2380 FORMAT  (20X*NO OF TRANS. CONST. OR WARPING JOINTS/MILE*
     1             * FOR CRCP* 4X, I8)
      IF (NJM .EQ. 0) XNJM = 10.**10.
C
      WRITE (6,2390) DFTY, CLW, CERR, CMAT, PSVGE, WL, NLT, RINT
 2390 FORMAT  (/  ,37X,*MAINTENANCE, DIMENSIONS AND MISCELLANEOUS* //
     1        20X*DAYS OF FREEZING TEMPERATURE PER YEAR    *14X,F8.2/
     2        20X*COMPOSITE LABOR WAGE FOR MAINTENANCE OPERATIONS*,
     3                                                    08X,F8.2/
     4        20X*COMPOSITE EQUIPMENT RENTAL RATE FOR MAINT OPERATIONS*
     5                                                    03X,F8.2/
     6        20X*COST OF MATERIALS FOR MAINTENANCE OPERATIONS*
     7                                                    11X,F8.2/
     8        20X*SALVAGE PERCENT AT THE END OF ANALYSIS PERIOD*
     9                                                    10X,F8.2/
     1        20X*WIDTH OF EACH LANE                       *14X,F8.2/
     2        20X*TOTAL NUMBER OF LANES IN BOTH DIRECTIONS *14X,I6/
     3        20X,*RATE OF INTEREST OR TIME VALUE OF MONEY* 16X,F8.2 )
C
C        INITIALIZING
C
         NN = 0
         JJ = 0
         NREQ = PSN4
         KSUB = 0
         NNT = 0
         KLIF = 0
         NNC = 0
         KLIFE = 0
         KREJ = 0
         NNR = 0
         KFUND = 0
         NR1 = 0
         MORI = NCS2
         NCS12 = NCS1+NCS2
         NOIN = 0
         KANAL = 0
C
      DO 2400 L = 1, 4
         NTHT(L) = 0
         LFT(L) = 0
         MANT(L) = 0
         NTOCT(L) = C
         NTMT(L) = 0
         NCNT(L) = 0
         NDLT(L) = 0
         NTOTR(L) = 0
         NTOT(L) = 0
         KIN(L) = 0
 2400 CONTINUE
C
         NREQ1 = NREQ+1
         NREQ5 = NREQ+5
      DO 2410 KLM = NREQ1, NREQ5
 2410    TCT(KLM) = 10000.0
C
         CTSP = CPLMSG*3.0/(1760.0*WL)
C
      IF (NCS1 .EQ. 2) GO TO 2420
         XJ = 3.2
         IDPV = 1
      GO TO 2430
 2420    XJ = 2.2
         IDPV = 2
C
 2430    THCC = TCMIN
C
         KIND = 0
```

```
             NOS = 0
             KTHCK = 0
          DO 2440 I = 1, NSB
          IF ((TCMIN+TSMIN(I)) .GT. TMAX) KTHCK = KTHCK+1
             SON = (TSMAX(I)-TSMIN(1))/SINC(I)
             NON = SON
             SONS = NON
          IF (SON .GT. SONS) NON = NON+1
             NOS = NOS+NON+1
 2440     CONTINUE
C
             NOC = 0
          DO 2450 I = 1, NC
             SON = (TCMAX-TCMIN)/CINC
             NON = SON
             SONS = NON
          IF (SON .GT. SONS) NON = NON+1
             NOC = NOC+NON+1
 2450     CONTINUE
C
             NOID = NOS*NOC
             NOIN = NOIN+NOID
C
          IF (KTHCK .LT. NSB) GO TO 2470
      WRITE (6,2460)
 2460 FORMAT  ( /,20X,45H*********************************************
     1           /,20X,45H*     NO COMBINATION OF CONCRETE AND        *
     2           /,20X,45H*     SUBBASE THICKNESSES IS POSSIBLE       *
     3           /,20X,45H*       EVEN AT THEIR MINIMUM LEVELS        *
     4           /,20X,45H*                                           *
     5           /,20X,45H*            PROGRAM  TERMINATED            *
     6           /,20X,45H*********************************************)
          GO TO 4650
C
 2470     CONTINUE
C
          DO 2480 J = 1, NSB
          IF ((THCC+TSMIN(J)) .LE. TMAX) GO TO 2490
 2480     CONTINUE
          GO TO 2510
C
C                 COMPUTING EQUIVALENT 18 KIP SINGLE ALXE LOADS
C
C         COMPUTE SERVICEABILITY TERM
 2490        GT = ALOG10((P1-P2)/(P1-1.5))
C
C         BETA FOR 18-KIP, SINGLE AXLE LOAD
             B18 = 1.+3.63*19.**5.20/(THCC+1.)**8.46
C
             WT = 0
          DO 2500 I = 1, NL
             XN = AVGL(I)+NCODE(I)
C
C         CALCULATE BETA FOR EACH AXLE LOAD GROUP
             B(I) = 1.+3.63*XN**5.20/(THCC+1.)**8.46
C
C         CALCULATE EQUIVALENCY FACTOR FOR EACH LOAD GROUP
             EQ(I) = (XN/19.)**4.62*10.**(GT/B18-GT/B(I))/NCODE(I)
     1           **3.28
C
C         CALCULATE TOTAL EQUIVALENT 18-KIP AXLES
             WT = WT+NA(I)*EQ(I)
 2500     CONTINUE
C
C         INCLUDE GROWTH AND DISTRIBUTION FACTORS
             WT = WT*365.0*DFL*DDF/(10.0**4)
             WT = WT*(1.0+AGF*AP/200.0)
             WT = WT*AP
C         WT     TOTAL 18 KIP SINGLE AXLES FOR ENTIRE ANALYSIS PERIOD
C
C         COMPUTE FINAL ADT
             ADTF = ADT*(1.+ADTGR/100.*AP)
C         ADTF   FINAL ADT
C
 2510        KLFCK = 0
C         KLFCK  CUTS THE INITIAL DESIGNS AFTER FINDING THAT INITIAL
C                LIFE FOR ALL CONCRETE AND SUBBASE TYPES IS MORE THAN
C                THE ANALYSIS PERIOD
C
          DO 3270 I = 1, NC
             MNOC = I
             CTC = 3.0/(1760.0*WL)*(CIC(I)+CSC(I))+CPCYC(I)/36.
     1           *THCC
C
          DO 3270 J = 1, NSB
             MNOS = J
             KRCK = 0
C         KRCK   CHECKS THE REINFORCEMENT FROM BEING DESIGNED MORE
C                THAN ONCE WITH THE INCREMENTS OF SUBBASE THICKNESS
C
             THSB = TSMIN(J)
             THMAX = TSMAX(J)
C
 2520     IF ((THCC+THSB) .LE. TMAX) GO TO 2530
             KREJ = KREJ+1
          GO TO 3260
C
 2530        KSUB = KSUB+1
C         KSUB   IS A COUNTER TO GIVE THE NUMBER OF SUCH DESIGNS
C                ( OUT OF ALL THE POSSIBLE DESIGNS) WHICH DO MEET THE
C                MINIMUM INITIAL THICKNESS REQUIREMENT
C
             CTSB = CPCYS(J)/36.0*THSB+CIS(J)*3.0/(1760.0*WL)
C
             ESJ = ES(J)
             EEF = EF(J)
C
C         START EQUATIONS FOR FINDING K AT THE TOP OF THE SUBBASE
C
          IF (THSB .EQ. 0.0) GO TO 2570
C
             E1 = (ALOG10(ESJ)-5.05)/0.35
```

```
            E2 = E1**2-4.0
            E3 = 1.0/8.0*(E1**3-7.0*E1)
            M1 = (SGE-8100.)/1500.
            M2 = 1.0/6.0*(3.0*M1**2-35.0)
            M3 = 1.0/24.0*(5.0*M1**3-101.0*M1)
C
      IF (THSB .LT. 6.0) GO TO 2540
      IF (THSB .LE. 12.0) GO TO 2550
      GO TO 2560
C
 2540       T1 = (THSB-3.0)/3.0
            T2 = 3.0*T1**2-2.0
            TOPK = 385.76202+69.6978*T1+8.58994*T2+27.06117*E1
     1            +3.98285*E2+5.55074*E3+66.48248*M1-1.60374*M2
     2            +0.43241*M3+31.07086*T1*E1+4.40539*T1*E2+5.05764
     3            *T1*E3+7.08264*T1*M1-2.35151*T1*M2+4.00969*T2
     4            *E1+0.42254*T2*E2+1.12694*T2*M1+3.55564*E1*M1
     5            -0.38658*E1*M2+0.36171*E2*M1-0.19788*E2*M2+1.05619
     6            *E3*M1+4.21905*T1*E1*M1-0.45553*T1*E1*M2+0.47169
     7            *T1*E2*M1-0.17973*T1*E2*M2+0.66341*T2*E1*M1
     8            +0.10999*T2*E2*M1+0.13451*E1*M3+0.13786*T1*E1
     9            *M3+0.24915*T1*M3
      GO TO 2580
C
 2550       T1 = (THSB-9.0)/3.0
            T2 = 3.0*T1**2-2.0
            TOPK = 578.61706+115.16060*T1+108.03355*E1+13.39099
     1            *E2+13.09083*E3+88.39701*M1-7.08938*M2+1.34638
     2            *M3+45.94402*T1*E1+4.57328*T1*E2+2.92403*T1
     3            *E3+13.81048*T1*M1-2.9967*T1*M2+0.58481*T1*M3
     4            +15.35524*E1*M1-1.45862*E1*M2+0.39667*E1*M3
     5            +1.54525*E2*M1-0.45022*E2*M2+0.07024*E2*M3+2.35879
     6            *E3*M1+6.92728*T1*E1*M1-0.56362*T1*E1*M2+0.12992
     7            *T1*E1*M3+0.60521*T1*E2*M1-0.09651*T1*E2*M2
     8            +0.59329*T2
      GO TO 2580
C
 2560       T1 = (THSB-15.0)/3.0
            T2 = 3.0*T1**2-2.0
            TOPK = 810.62222+115.98810*T1+200.53012*E1+23.20865
     1            *E2+18.74713*E3+116.49854*M1-13.38744*M2+2.6625
     2            *M3+46.53836*T1*E1+5.34689*T1*E2+2.75181*T1
     3            *E3+14.18543*T1*M1-3.30254*T1*M2+0.71233*T1
     4            *M3+29.34840*E1*M1-2.93899*E1*M2+0.73782*F1
     5            *M3+2.99806*E2*M1-0.72239*E2*M2+0.16778*E2*M3
     6            +3.19113*E3*M1-0.53567*E3*M2+7.08050*T1*E1*M1
     7            -0.92383*T1*E1*M2+0.19601*T1*E1*M3+0.88196*T1
     8            *E2*M1-0.16666*T1*E2*M2
      GO TO 2580
C
 2570       TOPK = SGE/23.925
            EEF = EFSG
C
C
C     START EQUATIONS FOR FINDING K AT THE TOP AFTER ERODABILITY
C
 2580 IF (EEF .EQ. 0.0) GO TO 2590
C
            EF1 =  EEF
            EF2 = (EF1**2-5.0)/4.0
            EF3 = (5.0*EF1**3-41.0*EF1)/12.0
            XLK = ALOG10(TOPK)
            XLOK = 10.0*(XLK-2.3)
            XLOK2 = (XLOK**2-21.0)/4.0
            XLOK3 = (XLOK**3-37.0*XLOK)/12.0
C
            TOPKEL = 1.68537-0.21029*EF1+0.00681*EF2+0.02305
     1            *EF3+0.08057*XLOK+0.00478*XLOK2+0.00175*XLOK3
     2            -0.01030*EF1*XLOK-0.00151*EF1*XLOK2-0.00583
     3            *EF2*XLOK-0.00548*EF2*XLOK2+0.00563*EF3*XLOK
     4            +0.00382*EF3*XLOK2+0.00116*EF3*XLOK3-0.00188
     5            *EF2*XLOK3-0.00043*EF1*XLOK3
            TOPKE = 10.0**TOPKEL
      GO TO 2600
C
 2590       TOPKE = TOPK
C
C     THIS FINISHES THE TREATMENT OF K VALUE
C
 2600 IF (TOPKE .LT. 5.0) TOPKE = 5.0
C
            PL(1) = 0.0
   CALL LIFE (P1, BONE, THCC, PL(2), SXD(I), E(I), PL(1))
C
      IF (PL(2) .GE. OFMIN) GO TO 2610
            KLIFE = KLIFE+1
C     KLIFE  COUNTER OF DESIGNS REJECTED BY INITIAL LIFE RESTRAINT
      GO TO 3260
C
 2610       KLIF = KLIF+1
C     KLIF  IS THE MUNBER OF SUCH DESIGNS WHICH PASSED THF TIMF TO
C     THE FIRST OVERLAY RESTRAINT
C
            PL(1) = 0.0
            PLP = PL(2)
      IF (PLP .GE. AP) PLP = AP
   CALL MANCE (PL(1), PLP, COMAN(1))
C
            KRCK = KRCK+1
C     KRCK  PREVENTS THE STEEL FROM BEING DESIGNED MORE THAN ONCE
C            WITH AN INCREASE IN THICKNESS OF THE SAME SUBRASE
      IF (KRCK .GT. 1) GO TO 2910
C
            IDRF = 1
            CTRJB = 0.0
            CTLSB = 0.0
            JN = 0
            JM = 0
            JP = 0
C
            XNLT = NLT
            WIDTH = XNLT*WL
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            XNJN = NJNT
      IF (MODEL-2) 2840,2840,2620
 2620       WIDTH = WIDTH/2.0
            NJNT = NLT-2
            XNJN = NJNT
C
      IF (XJ .NE. 3.2) GO TO 2700
            CTRJ = 1000.
      IF (NCS3 .EQ. 2) GO TO 2660
C
      DO 2650 ISTEEL = 1, KOUNT1
            SPATJ = SLV
 2630       ASPFW = THCC/24.*WC(I)*SPATJ*FFSB(J)/(TYSBS(ISTEEL)
     1            *0.75)
            COSTLS = 12.0*ASPFW*CPPBS(ISTEEL)*490.0/1728.0
            COSTTJ = CPFTJ/SPATJ
            CTLRTJ = COSTLS+COSTTJ
      IF (CTLRTJ .GE. CTRJ) GO TO 2640
            CTRJ = CTLRTJ
            CTLS = COSTLS
            CTTJ = COSTTJ
            ASPF = ASPFW
C     ABOVE COSTS ARE PER SQ FT AND AREA OF STEEL IS PER FT WIDTH
            MNOLR = ISTEEL
            SPTJ = SPATJ
 2640 IF (SPATJ .EQ. SUV) GO TO 2650
            SPATJ = SPATJ+10.
      IF (SPATJ .GT. SUV) SPATJ = SUV
      GO TO 2630
 2650 CONTINUE
C
            CTRJB = CTRJ
C
      IF (NCS3 .EQ. 1) GO TO 2740
C
 2660 DO 2690 IMESH = 1, KOUNT3
C
            SPATJ = SLV
 2670       ASPFW = THCC/24.*WC(I)*SPATJ*FFSB(J)/(TYSWS(IMESH)
     1            *0.75)
            COSTLS = 12.0*ASPFW*CPPWS(IMESH)*490.0/1728.0
            COSTTJ = CPFTJ/SPATJ
            CTLRTJ = COSTLS+COSTTJ
      IF (CTLRTJ .GE. CTRJ) GO TO 2680
            CTRJ = CTLRTJ
            CTLS = COSTLS
            CTTJ = COSTTJ
            ASPF = ASPFW
            MNOLR = IMESH
            SPTJ = SPATJ
 2680 IF (SPATJ .EQ. SUV) GO TO 2690
            SPATJ = SPATJ+10.
      IF (SPATJ .GT. SUV) SPATJ = SUV
      GO TO 2670
 2690 CONTINUE
C
      IF (CTRJ .EQ. CTRJB) GO TO 2740
C
C     FOR JCP AND CRCP BOTH THE PROGRAM DESIGNS THE BARS IF
C     THE COSTS OF MESHES AND BARS HAPPEN TO BE THE SAME
C     WHEN BOTH TYPES OF REINFORCEMENT ARE TO BE TRIED
C
            IDRF = 2
      GO TO 2800
C
 2700       CTLS = 1000.0
            ASLIM = 0.4*12.0*THCC/100.0
C
      IF (NCS3 .EQ. 2) GO TO 2720
C
      DO 2710 ISTEEL = 1, KOUNT1
            ASPFW = 12.0*THCC*(1.3-0.2*FFSB(J))*TS(I)/(0.75*
     1            TYSBS(ISTEEL))
      IF (ASPFW .LT. ASLIM) ASPFW = ASLIM
            COSTLS = 12.0*ASPFW*CPPBS(ISTEEL)*490.0/1728.0
      IF (COSTLS .GE. CTLS) GO TO 2710
            CTLS = COSTLS
            ASPF = ASPFW
            MNOLR = ISTEEL
 2710 CONTINUE
C
            CTLSB = CTLS
C
      IF (NCS3 .EQ. 1) GO TO 2740
C
 2720 DO 2730 IMESH = 1, KOUNT3
            ASPFW = 12.0*THCC*(1.3-0.2*FFSB(J))*TS(I)/(0.75*TYSWS(IME
     1            SH))
      IF (ASPFW .LT. ASLIM) ASPFW = ASLIM
            COSTLS = 12.0*ASPFW*CPPWS(IMESH)*490./1728.
      IF (COSTLS .GE. CTLS) GO TO 2730
            CTLS = COSTLS
            ASPF = ASPFW
            MNOLR = IMESH
 2730 CONTINUE
C
      IF (CTLS .LT. CTLSB) GO TO 2800
C
 2740 DO 2770 ISP = 1, KOUNT6
            SPAC(ISP) = 3.0/64.0*3.14159*(BARN(ISP))**2.0/ASPF
      IF (XJ-3.2) 2750,2760,2760
 2750       BOND = 3.14159*BARN(ISP)/(8.0*SPAC(ISP)*THCC)
      IF (BOND .LT. 0.03) GO TO 2770
 2760       JN = JN+1
            SPACL(JN) = SPAC(ISP)
            DIAL(JN) = BARN(ISP)
 2770 CONTINUE
C
            CTTS = 1000.0
      DO 2780 ISTEEL = 5, KOUNT2
            ATSF = THCC/24.0*WC(I)*WIDTH*FFSB(J)/(TYSBS(ISTEEL)
     1            *0.75)
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            COSTTS = 12.0*ATSF*CPPBS(ISTEEL)*490.0/1728.0
      IF (COSTTS .GE. CTTS) GO TO 2780
            CTTS = COSTTS
            ATSPF = ATSF
            MNOTR = ISTEEL
 2780 CONTINUE
C
      DO 2790 ISP = 1, KOUNT6
            SPAC(ISP) = 3.0/64.0*3.14159*(BARN(ISP))**2.0/ATSPF
            JM = JM+1
            SPACT(JM) = SPAC(ISP)
            DIAT(JM) = BARN(ISP)
 2790 CONTINUE
C
            JP = JM
            CTTBR = XNJN*ATSPF*60.0*DIAT(1)/8.0*CPPBS(MNOTR)
     1            *490.0/1728.0*1.0/(XNLT*WL)
C     COST OF TIE BARS IS CALCULATED FROM FIRST TIE BAR PRINTED
C
            CTRF = (CTLS+CTTS)*9.0
C
            CTTB = CTTBR*9.0
      GO TO 2880
C
 2800       IDRF = 2
      DO 2830 ISP = 1, KOUNT4
            DIAM(ISP) = (ASPF*SL(ISP)/(3.0*3.14159))**0.5
      IF (XJ-3.2) 2810,2820,2820
 2810       BOND = 3.14159*DIAM(ISP)/(SL(ISP)*THCC)
      IF (BOND .LT. 0.03) GO TO 2830
 2820       JN = JN+1
            SPACL(JN) = SL(ISP)
            DIAL(JN) = DIAM(ISP)
 2830 CONTINUE
C
 2840       ATSPF = THCC/24.0*WC(1)*WIDTH*FFSB(J)/TYSWS(MNOLR)
     1            *4.0/3.0
            CTTS = 12.0*ATSPF*CPPWS(MNOLR)*490.0/1728.0
            MNOTR = MNOLR
      DO 2850 ISP = 1, KOUNT4
            DIAM(ISP) = (ATSPF*ST(ISP)/(3.0*3.14159))**0.5
            JM = JM+1
            SPACT(JM) = ST(ISP)
            DIAT(JM) = DIAM(ISP)
 2850 CONTINUE
C
            CSTTB = 1000.0
      DO 2860 ITB = 1, KOUNT5
            ATBPF(ITB) = THCC/24.0*WC(1)*WIDTH*FFSB(J)/TYSTS(ITB)
     1            *4.0/3.0
            COSTTB = 12.0*ATBPF(ITB)*CPPTS(ITB)*490.0/1728.0
      IF (COSTTB .GE. CSTTB) GO TO 2860
            CSTTB = COSTTB
            ATB = ATBPF(ITB)
            MNOTB = ITB
 2860 CONTINUE
C
      DO 2870 JPP = 1, KOUNT7
            JP = JP+1
            SPTIF(JPP) = 3.0/64.0*3.14159*(TBARN(JPP))**2.0/ATB
 2870 CONTINUE
            CTTBR = XNJN*ATBPF(1)*60.0*TBARN(1)/8.0*CPPTS(1)
     1            *490.0/1728.0*1.0/(XNLT*WL)
C
            CTRF = (CTLS+CTTS)*9.0
            CTTB = CTTBR*9.0
C
 2880 CONTINUE
C
      IF (XJ-3.2) 2890,2900,2900
 2890       CTJ = XNJN*CPFLJ/(XNLT*WL)*9.0+NJM/1760.0*3.0*CPFTJ
            SPTJ = 5280.0/XNJM
      GO TO 2910
C
 2900       CTJ = (XNJN*CPFLJ/(XNLT*WL)+CTTJ)*9.0
C
 2910       CTIN = CTSP+CTC+CTSB+CTRF+CTJ+CTTB
C     CTIN  INITIAL COST
      IF (CTIN .GT. CMAX) GO TO 3260
C
            KFUND = KFUND+1
C     KFUND  IS THE NUMBER OF SUCH DESIGNS WHICH PASS THE
C              RESTRAINT OF THE MAXIMUM INITIAL FUNDS AVAILABLE
C     KIND   IS THE NUMBER OF DESIGNS WHICH PASS ALL RESTRAINTS
C              WITHIN EACH COMBINATION
C
            LM = 0
      IF ((NCS1 .EQ. 0) .AND. (XJ .EQ. 2.2)) LM = 1
      IF ((XJ .EQ. 2.2) .AND. (NCS2 .EQ. 0)) LM = 2
      IF ((NCS2 .EQ. 0) .AND. (NCS1 .NE. 0)) LM = 0
C
      IF (PL(2) .LT. AP) GO TO 2920
          L = 1
          LPL = L + 1
          IDOV = 3
          KLFCK = KLFCK+1
          KANAL = KANAL+1
          COTR(1) = 0.0
          COSOV(1) = 0.0
          THOVT(1) = 0.0
          CTSC = 0.0
          THOV(1) = 0.0
          PL(1) = 0.0
      GO TO 3090
 2920 IF (OFMIN.GE.AP)  GO TO 3260
            KIND = KIND + 1
 2930     NTHICK = 0
          NTIME = 0
          NDUEL = 0
          NCONS = 0
          LIFCAL = 0
          NTDCCAL = 0
```

```
          MANCAL = 0
          COTR(1) = 0.0
          COSOV(1) = 0.0
          THOV(1) = 0.0
          THOVT(1) = 0.0
          PL(1) = 0.0
          CTSC = 0.0
C
          BONY(2) = BONE
          BONY(1) = 0.1234
          XINCR = 0.5
C
      IF (NCS2 .EQ. 1) GO TO 2940
          OMIN = OMINA
          OMAX = OMAXA
C
          E11 = (ACE-450000.0)/250000.0
          E22 = 3.0*E11**2-2.0
          D11 = THCC-9.0
          D22 = 1.0/4.0*(D11**2-5.0)
          D33 = 1.0/12.0*(5.0*D11**3-41.0*D11)
          K11 = (ALOG10(TOPKE)-2.30103)/0.69897
          K22 = 3.0*K11**2-2.0
C
          EFOV = 11.77033+0.79408*E11-0.05925*E22+0.93256*D11
     1         +0.032*D22+0.5545*K11+0.1155*K22-0.01952*E11
     2         *D11-0.15887*E11*K11-0.02921*E11*K22+0.00713
     3         *E22*D11+0.01438*E22*K11-0.03193*D11*K11-0.02356
     4         *D11*K22+0.043*D22*K11+0.01433*D22*K22+0.02228
     5         *E11*D11*K11+0.00814*E11*D11*K22-.02238*E11
     6         *D22*K11
C
      GO TO 2950
 2940     OMIN = OMINC
          OMAX = OMAXC
 2950     L = 1
 2960     L = L+1
      IF (L-9) 2980,2980,2970
C
 2970     NDUEL = NDUEL+1
C     NDUEL    IS THE NUMBER OF TIMES THE TOTAL NUMBER OF OVERLAYS
C     REQUIRED WERE MORE THAN THE MAXIMUM NUMBER SPECIFIED
      GO TO 3010
C
 2980     THOV(L) = OMIN
 2990     THOVT(L) = THOVT(L-1)+THOV(L)
      IF (THOVT(L) .GT. OMAX) GO TO 3000
          BONY(L+1) = BONY(L)*EXP(-BONY(L)*(PL(L)-PL(L-1)))
      GO TO 3030
C
 3000     NTHICK = NTHICK+1
C     NTHICK   IS THE NUMBER OF TIMES THE MAXIMUM TOTAL OVERLAY
C     THICKNESS RESTRAINT WAS HIT WHILE THE STRATEGY WAS TRYING
C     TO REACH THE ANALYSIS PERIOD
C
C
 3010     L = L-1
      IF (L .EQ. 1) GO TO 3240
C     THE ABOVE STATEMENT QUITS THE OVERLAYING PROCEDURE FOR A
C     PARTICULAR INITIAL DESIGN. THIS WILL HAPPEN IN ANY OF THE
C     FOLLOWING CASES.
C        1. WHEN OVERLAY NUMBER 1 THICKNESS,PASSING THE THICKNESS
C           RESTRAINT IS SUFFICIENT TO LAST THE ANALYSIS PERIOD
C        2. WHEN THE OVERLAY NUMBER 1 THICKNESS HITS THE THICKNESS
C           RESTRAINT
C     OR 3. WHEN AFTER CONSIDERING A NUMBER OF SUCCESSFUL OVERLAY
C           STRATEGIES, THE PROGRAM REACHES ANY OF THE ABOVE STATED.
C
 3020     THOV(L) = THOV(L)+XINCR
      GO TO 2990
C     CALL LIFE TO CALCULATE THE LIFE OF THE PAVEMENT OVERLAY COMB.
 3030 IF (NCS2 .EQ. 1) GO TO 3040
C
          IDOV = 1
          T11 = (THOVT(L)-6.0)/3.0
          T22 = T11**2-3.0
          T33 = 1.0/6.0*(5.0*T11**3-17.0*T11)
C
          EFOT = 1.50661*T11+0.1104*T22-0.02239*T33+0.42692
     1         *T11*E11-0.03819*T11*E22-0.03936*T11*D11+0.01239
     2         *T11*D22+0.0083*T11*E11*D11*K11+0.25962*T11
     3         *K11+0.05293*T11*K22+0.02232*T22*E11-0.00796
     4         *T22*E22-0.00467*T22*D11-0.01509*T22*K11-0.01425
     5         *T33*E11-0.0087*T11*E11*D11-0.09388*T11*E11
     6         *K11-0.01642*T11*E11*K22+0.00422*T11*E22*D11
     7         -0.00864*T11*D11*K11-0.00937*T11*D11*K22
C
          DEFF = EFOV+EFOT
C
          CTOVER(L) = (CIOV*3.0/(1760.0*WL)+THOV(L)/36.0*CPCYAC)
     1         /((1.+RINT/100.0)**PL(L))
          COSOV(L) = COSOV(L-1)+CTOVER(L)
          HPSY = THOV(L)/(36.0*ACPR)
      GO TO 3050
C
C
 3040     IDOV = 2
          RR = THOVT(L)**1.4+COEF*THCC**1.4
          DEFF = RR**(1.0/1.4)
          COSOV(1) = 0.0
          CTOVER(L) = (3.0/(1760.0*WL)*(CIC(I)+CSC(I))+CPCYC(I)
     1         /36.*THOV(L))/((1.0+RINT/100.0)**PL(L))
          COSOV(L) = COSOV(L-1)+CTOVER(L)
          HPSY = THOV(L)/(36.0*CPR)
C
 3050 CALL LIFE (POV, BONY(L+1), DEFF, PP, SXD(I), E(I), PL(L))
          LIFCAL = LIFCAL+1
C     LIFCAL IS THE NUMBER OF TIMES LIFE SUBROUTINE IS CALLED
C
          PL(L+1) = PL(L)+PP
C
C     CALCULATE DELAY COSTS
```

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            COTR(1) = 0.0
      CALL TDC (PL(L), THOV(L), CTTRAF(L), HPSY)
            NTDCCAL = NTDCCAL+1
            COTR(L) = COTR(L-1)+CTTRAF(L)
C
            PLP = AP
         IF (PL(L+1) .LT. AP) PLP = PL(L+1)
C        CALCULATE MAINTENANCE FROM PL(L) TO P(L+1)
      CALL MANCE (PL(L), PLP, CTMAN(L))
            MANCAL = MANCAL+1
            COMAN(L) = COMAN(L-1)+CTMAN(L)
C
         IF (PL(L+1) .GE. AP) GO TO 3060
         IF (PP .GE. BOMIN) GO TO 2960
C
            NTIME = NTIME+1
C        NTIME  IS  NUMBER OF SUCH STRATEGIES WHICH WERE ABANDONED
C        BECAUSE TIME BETWEEN OVERLAYS AS CALCULATED AT ANY TIME
C        WAS LESS THAN THE MINIMUM SPECIFIED.
         GO TO 3020
 3060    CONTINUE
            LPL = L+1
         IF (IDOV .EQ. 2) GO TO 3090
C
            ONSEAL = CPLMS*3.0/(1760.0*WL)
            CTSC = 0.0
            NOSE = 0
         DO 3080 ISL = 3, LPL
            PLIS = PL(ISL)
         IF (PLIS .GT. AP) PLIS = AP
            TIME = PLIS-PL(ISL-1)
            SEAL = 0.0
 3070       TISL = TFS+SEAL*TBS
         IF (TISL .GT. TIME) GO TO 3080
            CTSC = CTSC+ONSEAL/((1.0+RINT/100.0)**(PL(ISL-1)
     1            +TISL))
            SEAL = SEAL+1.0
         GO TO 3070
 3080    CONTINUE
C
 3090       RISL = PSVGE/(100.0*(1.0+RINT/100.0)**AP)
         IF (IDOV-2) 3100,3110,3110
 3100       OVCOS = THOVT(L)/36.0*CPCYAC
         GO TO 3120
 3110       OVCOS = THOVT(L)/36.0*CPCYC(I)
 3120       CTSR = -(THCC/36.*CPCYC(1)+OVCOS)*RISL
C
            TCOST = CTIN+COSOV(L)+COTR(L)+COMAN(L)+CTSC+CTSR
     1            +CPSYR
C
            JJ = 0
         DO 3230 M = 1, 2
            NLM1 = NREQ+LM+1
         IF (IDOV .EQ. 3) NLM1 = NREQ+5
         IF (M .EQ. 2) GO TO 3130
         IF (TCOST .GT. TCT(NLM1)) GO TO 3230
            NN = NLM1
         GO TO 3140
C
 3130       NN = NN+1
            NR1 = NR1+1
         IF (NN .GT. NREQ) GO TO 3200
 3140    CONTINUE
C
            IP(NN) = IDPV
            IO(NN) = IDOV
            IR(NN) = IDRF
            TC(NN) = THCC
            MC(NN) = MNOC
            TSUB(NN) = THSB
            MS(NN) = MNOS
         DO 3150 KK = 1, JN
            RLS(NN, KK) = SPACL(KK)
 3150       RLN(NN, KK) = DIAL(KK)
            JNR(NN) = JN
            MLR(NN) = MNOLR
         DO 3160 KK = 1, JM
            RTS(NN, KK) = SPACT(KK)
 3160       RTN(NN, KK) = DIAT(KK)
            JMR(NN) = JM
            MTR(NN) = MNOTR
         DO 3170 KK = 1, JP
            TBSP(NN, KK) = SPTIE(KK)
 3170       TBN(NN, KK) = TBARN(KK)
            JPR(NN) = JP
            MTB(NN) = MNOTB
            STJ(NN) = SPTJ
         DO 3180 KK = 2, LPL
 3180       PLF(NN, KK) = PL(KK)
            PLF(NN, 13) = PL(LPL)
            NPP(NN) = L
         DO 3190 KK = 1, L
 3190       TO(NN, KK) = THOV(KK)
            SUMOV(NN) = THOVT(L)
            CSP(NN) = CTSP
            CC(NN) = CTC
            CSB(NN) = CTSB
            CR(NN) = CTRF
            CJ(NN) = CTJ
            CTB(NN) = CTTB
            CI(NN) = CTIN
            CO(NN) = COSOV(L)
            CT(NN) = COTR(L)
            CM(NN) = COMAN(L)
            CSEAL(NN) = CTSC
            CSR(NN) = CTSR
            CA(NN) = CPSYR
            TCT(NN) = TCOST
C
            NN = NR1
C
         IF (M .EQ. 1) GO TO 3230
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      GO TO 3230
C
 3200     TCTMAX = 0.0
      DO 3220 KUSM = 1, NREQ
      IF (TCT(KUSM) .GT. TCTMAX) GO TO 3210
      GO TO 3220
 3210     TCTMAX = TCT(KUSM)
          JAY = KUSM
 3220 CONTINUE
      IF (TCOST .GT. TCT(JAY)) GO TO 3230
          NN = JAY
      GO TO 3140
C
 3230 CONTINUE
C
      IF (IDOV .EQ. 3) GO TO 3270
C
          NCONS = NCONS+1
C     NCONS  IS THE NUMBER OF SUCH STRATEGIES WHICH PASSED ALL TESTS
C     AND RESTRAINTS AND HIT THE ANALYSIS PERIOD. EACH STRATEGY
C     WILL MAKE ONE DESIGN IN COMBINATION WITH THE INITIAL DESIGN.
      GO TO 3010
C
 3240 CONTINUE
C
C
          LM = LM+1
          NTHT(LM) = NTHT(LM)+NTHICK
          LFT(LM) = LFT(LM)+LIFCAL
          NTDCT(LM) = NTDCT(LM)+NTDCCAL
          MANT(LM) = MANT(LM)+MANCAL
          NTMT(LM) = NTMT(LM)+NTIME
          NCNT(LM) = NCNT(LM)+NCONS
          NDLT(LM) = NDLT(LM)+NDUEL
          NTOTR(LM) = NTHT(LM)+NTMT(LM)+NDLT(LM)
          NTOT(LM) = NTOTR(LM)+NCNT(LM)
          KIN(LM) = KIND
C
      IF (NCS2 .NE. 0) GO TO 3250
          NCS2 = 1
      GO TO 2930
 3250     NCS2 = MOR1
C
 3260 IF (THSB .EQ. THMAX) GO TO 3270
          THSB = THSB+SINC(J)
      IF (THSB .GT. THMAX) THSB = THMAX
          MINTHCK = 0
      GO TO 2520
C
 3270 CONTINUE
C     ABOVE STATEMENT IS FOR SUBBASE TYPES AND CONCRETE TYPES LOOPS
C     AS WELL AS SUBBASE THICKNESS INCREMENTS.
C
          NCSB = NC*NSB
      IF (KLFCK .EQ. NCSB) GO TO 3280
C     KLFCK  HAS TO BE EQUAL TO NCSB BY CONSECUTIVE ADDITION TO
C     QUIT CONCRETE THICKNESS LOOP. OTHERWISE, THE DESIGN PROCESS
C     WILL GO ON IN THE NORMAL FASHION
C
      IF (THCC .EQ. TCMAX) GO TO 3280
          THCC = THCC+CINC
      IF (THCC .GT. TCMAX) THCC = TCMAX
      GO TO 2470
C
 3280 CONTINUE
      IF (XJ .EQ. 2.2) GO TO 3290
      IF (NCS1 .NE. 0) GO TO 3290
      GO TO 2420
C
 3290     LM = 2
      IF (NCS12 .EQ. 0) LM = 4
      IF (NCS12 .GT. 2) LM = 1
      IF ((NCS12 .EQ. 2) .AND. (NCS1 .EQ. 1)) LM = 1
      DO 3300 IS = 1, LM
          NNT = NNT+NTOT(IS)
          NNR = NNR+NTOTR(IS)
 3300     NNC = NNC+NCNT(IS)
C
      IF (KFUND .GT. 0) GO TO 3320
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,3310)
 3310 FORMAT  ( /,20X,45H*********************************************
     1           /,20X,45H*     OUT OF ALL COMBINATIONS TRIED          *
     2           /,20X,45H*           NO  INITIAL DESIGN               *
     3           /,20X,45H*        MEETS THE REQUIREMENTS              *
     4           /,20X,45H*                                            *
     5           /,20X,45H*           PROGRAM TERMINATED               *
     6           /,20X,45H*********************************************)
      GO TO 4530
C
 3320 IF (NNC .GT. 0) GO TO 3340
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,3330)
 3330 FORMAT  ( /,20X,45H*********************************************
     1           /,20X,45H*     OUT OF ALL OVERLAY STRATEGIES          *
     2           /,20X,45H*             THAT WERE TRIED                *
     3           /,20X,45H*         NO  OVERLAY  STRATEGY              *
     4           /,20X,45H*         MEETS THE REQUIREMENTS             *
     5           /,20X,45H*                                            *
     6           /,20X,45H*    PROGRAM PARTIALLY CONTINUED             *
     7           /,20X,45H*********************************************)
      GO TO 3710
C
 3340 DO 3710 IRK = 1, LM
          NN = NREQ+IRK
      WRITE (6,1030) NPROB, TITLE
C
      IF (KIN(IRK) .GT. 0) GO TO 3360
      WRITE (6,3350)
 3350 FORMAT  ( /,20X,45H*********************************************
     1           /,20X,45H*         NO INITIAL DESIGN POSSIBLE         *
     2           /,20X,45H*           FOR THIS COMBINATION             *
     3           /,20X,45H*                                            *
     4           /,20X,45H*         PROGRAM WILL BE  CONTINUED         *
     5           /,20X,45H*         FOR THE OTHER COMBINATIONS         *
     6           /,20X,45H*********************************************)
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```
      GO TO 3710
C
 3360    IF (NCNT(IRK) .GT. 0) GO TO 3380
      WRITE (6,3370)
 3370 FORMAT  ( /,20X,45H*********************************************
     1         /,20X,45H*                                           *
     2         /,20X,45H*       NO OVERLAY STRATEGY POSSIBLE        *
     3         /,20X,45H*             FOR THIS COMBINATION          *
     4         /,20X,45H*                                           *
     5         /,20X,45H*       PROGRAM WILL BE  CONTINUED          *
     6         /,20X,45H*       FOR THE OTHER COMBINATIONS          *
     7         /,20X,45H*********************************************)
      GO TO 3710
C
 3380         IDPVR = IP(NN)
              IDOVR = IO(NN)
              IDRFR = IR(NN)
              NPPR = NPP(NN)
C
      WRITE (6,3390) PVID(IDPVR), OVID(IDOVR), PLF(NN, 2), TC(NN),
     1      MC(NN), TSUB(NN), MS(NN)
 3390 FORMAT  (/,15X *MOST ECONOMICAL *,A3,* PAVEMENT DESIGN *
     1        *WITH *,A4,* OVERLAY * // 10X, *INITIAL CONSTRUCTION, *
     2        *  LIFE IS * F7.3 * YEARS * // 13X *MATERIALS* 43X
     3        *DESCRIPTION * / 61X  *MATERIAL    MATERIAL * /
     4        62X *NUMBER* 7X *NAME* // 13X *CONCRETE    *
     5        F8.2 * INCHES* 25X, I1 /    13X *SUBBASE     *
     6        F8.2 * INCHES* 25X, I1            )
              JNRN = JNR(NN)
              MLRN = MLR(NN)
              JMRN = JMR(NN)
              MTRN4 = MTR(NN)-4
              MTRN = MTR(NN)
              JPRN = JPR(NN)
              MTBN = MTB(NN)
C
C        BAR REINFORCEMENT
         IF (IDRFR .EQ. 2) GO TO 3440
         IF (JNRN) 3420,3400
 3400 WRITE (6,3410)
 3410 FORMAT  ( 13X*LONG. REINF. BAR SPACING NOT AVAILABLE DUE TO BOND*)
         GO TO 3430
 3420 WRITE (6,3490) (RLN(NN, I), I = 1, JNRN)
      WRITE (6,3510) MLRN, (NAMEBS(MLRN, I), I = 1, 3)
      WRITE (6,3500) (RLS(NN, I), I = 1, JNRN)
 3430 WRITE (6,3520) (RTN(NN, I), I = 1, JMRN)
      WRITE (6,3510) MTRN4, (NAMEBS(MTRN, I), I = 1, 3)
      WRITE (6,3500) (RTS(NN, I), I = 1, JMRN)
      WRITE (6,3560) (RTN(NN, I), I = 1, JMRN)
      WRITE (6,3510) MTRN4, (NAMEBS(MTRN, I), I = 1, 3)
      WRITE (6,3500) (RTS(NN, I), I = 1, JMRN)
         GO TO 3570
C
C        MESH REINFORCEMENT
 3440    IF (JNRN) 3470,3450
 3450 WRITL (6,3460)
 3460 FORMAT  (13X*LONG. REINF. MESH DIAMETER NOT AVAILABLE DUE TO BOND*
     1)
         GO TO 3480
 3470 WRITE (6,3530) (RLS(NN, I), I = 1, JNRN)
      WRITE (6,3510) MLRN, (NAMEWS(MLRN, I), I = 1, 3)
      WRITE (6,3540) (RLN(NN, I), I = 1, JNRN)
 3480 WRITE (6,3550) (RTS(NN, I), I = 1, JMRN)
      WRITE (6,3510) MTRN, (NAMEWS(MTRN, I), I = 1, 3)
      WRITE (6,3540) (RTN(NN, I), I = 1, JMRN)
      WRITE (6,3560) (TBN(NN, I), I = 1, JPRN)
      WRITE (6,3510) MTBN, (NAMETS(MTBN, I), I = 1, 3)
      WRITE (6,3500) (TBSP(NN, I), I = 1, JPRN)
 3490 FORMAT  (13X *LONG. REINF.    BAR NO.* 4F6.0 )
 3500 FORMAT  (29X                  *SPACING* 4F6.1 )
 3510 FORMAT  (1H+, 64X, I1, 5X, 2A4, A2 )
 3520 FORMAT  (13X *TRAN. REINF.    BAR NO.* 4F6.0 )
 3530 FORMAT  (13X *LONG.REINF.MESH SPACING* 4F6.1 )
 3540 FORMAT  (23X            *MESH DIAMETER* 4F6.2 )
 3550 FORMAT  (13X *TRAN.REINF.MESH SPACING* 4F6.1 )
 3560 FORMAT  (13X *TIE BARS     BAR NUMBER* 4F6.0 )
 3570    CONTINUE
C
              ISTJ = STJ(NN)
      WRITE (6,3580) ISTJ
 3580 FORMAT  ( / 25X *TRANSVERSE JOINT SPACING  *  I5  * FEET * )
      WRITE (6,3590) WL
 3590 FORMAT  ( 25X *LONGITUDINAL JOINT SPACING* F5.0 * FEET * )
      WRITE (6,3600)
 3600 FORMAT  ( // 10X *SUBSEQUENT CONSTRUCTION * )
         DO 3610 KK = 2, NPPR
              KPRINT = KK-1
 3610 WRITE (6,3620) (KPRINT, TO(NN, KK), OVID(IDOVR), PLF(NN, KK))
 3620 FORMAT  (13X, I1, *  OVERLAY WITH * F5.2 * INCHES OF *
     1        A4 * AFTER * F7.3 * YEARS * )
      WRITE (6,3630) SUMOV(NN), PLF(NN, NPPR+1)
 3630 FORMAT  ( / 15X *TOTAL OVERLAY THICKNESS * F6.2 * INCHES*
     1        *     TOTAL LIFE * F7.3 * YEARS * )
      WRITE (6,3640) CSP(NN), CC(NN), CSB(NN), CR(NN), CJ(NN)
 3640 FORMAT  ( // 10X *COST ANALYSIS    DOLLARS PER SQUARE YARD *
     1        /    15X *INITIAL CONSTRUCTION * /
     2        18X *COST OF SUBGRADE PREPARATION*  16X, F6.3 /
     3        18X *COST OF CONCRETE            *  16X, F6.3 /
     4        18X *COST OF SUBBASE             *  16X, F6.3 /
     5        18X *COST OF REINFORCEMENT       *  16X, F6.3 /
     6        18X *COST OF JOINTS              *  16X, F6.3 )
      WRITL (6,3650) CTB(NN)
 3650 FORMAT  (18X *COST OF TIE BARS           * 16X, F6.3 / )
      WRITE (6,3660) CI(NN), CO(NN), CT(NN), CM(NN)
 3660 FORMAT  (15X*TOTAL INITIAL CONSTRUCTION COST          *07X,F6.3/
     1        15X *TOTAL OVERLAY CONSTRUCTION COST          *07X,F6.3/
     2        15X *TOTAL T.D. COST DURING OV. CONSTRUCTION *07X,F6.3/
     3        15X *TOTAL MAINTENANCE COST                  *07X,F6.3)
```

```
      IF (IDOVR .EQ. 1) WRITE (6,3670) CSEAL(NN)
 3670 FORMAT  (15X*TOTAL SEAL COAT COST AFTER OV. CONSTRUCTION*
     1        4X, F6.3 )
      WRITE (6,3680) CSR(NN)
 3680 FORMAT  (15X*SALVAGE RETURNS*  32X, F6.3 )
         IF (CA(NN) .NE. 0.0) WRITE (6,3690) CA(NN)
 3690 FORMAT  (15X*ANY ADDITIONAL COST SPECIFIED* 18X, F6.3 )
C
            JERK = NOID-KIN(IRK)
      WRITE (6,3700) TCT(NN), NOID, JERK, KIN(IRK), NCNT(IRK)
 3700 FORMAT  (/ 14X *TOTAL OVERALL COST*  30X, F6.3 //
     1         10X *DESIGN ANALYSIS * /
     2        13X *TOTAL* 14* INITIAL DESIGNS WERE EXAMINED, OUT OF *
     3        *WHICH, * / 18X, I4   * DESIGNS WERE REJECTED DUE TO *
     4        *USER RESTRAINTS * / 18X, I4* REMAINING INITIAL DESIGNS*
     5        * PRODUCED  * I3* OVERLAY STRATEGIES* )
 3710     CONTINUE
          IF (KANAL .EQ. 0) GO TO 3750
            NN = NREQ + 5
            IDPVR = IP(NN)
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,3720) PVID(IDPVR), TC(NN), MC(NN), TSUB(NN), MS(NN)
 3720 FORMAT  ( /,15X *MOST ECONOMICAL INITIAL DESIGN LASTING THE *
     1         *ANALYSIS PERIOD*  //, 13X *PAVEMENT TYPE IS * A3 /
     2         /, 54X*MATERIAL* /, 55X*NUMBER   *
     3         /, 13X  *CONCRETE    * F8.2 * INCHES * 17X, I1,
     4         /, 13X  *SUBBASE     * F8.2 * INCHES * 17X,  I1  )
            ISTJ = STJ(NN)
      WRITE (6,3580) ISTJ
      WRITE (6,3590) WL
      WRITE (6,3635)  PLF(NN,13)
 3635 FORMAT  (//,13X*LIFE OF THE DESIGN IS *F7.3* YEARS*)
      WRITE (6,3640) CSP(NN), CC(NN), CSB(NN), CR(NN), CJ(NN)
      WRITE (6,3650) CTB(NN)
      WRITE (6,3730) CI(NN), CM(NN)
 3730 FORMAT  (15X*TOTAL INITIAL CONSTRUCTION COST *15X,F6.3/
     1         15X*TOTAL MAINTENANCE COST          *15X,F6.3 )
      WRITE (6,3680) CSR(NN)
          IF (CA(NN) .NE. 0.0) WRITE (6,3690) CA(NN)
      WRITE (6,3740) TCT(NN), KANAL
 3740 FORMAT  (/ 14X *TOTAL OVERALL COST* 30X, F6.3 //
     1         10X *DESIGN ANALYSIS * /       20X *THIS IS THE *
     2         *MOST OPTIMAL DESIGN * / 20X *OUT OF * I4 * ACCEPTABLE*
     3         * DESIGNS * / 20X *OF THIS KIND  *  )
 3750     CONTINUE
C
          IF (NR1 .LT. NREQ) NREQ = NR1
            TCTMM = -1.0
          DO 3770 J = 1, NREQ
            TCTMIN = 10.0**10.
          DO 3760 I = 1, NREQ
          IF (TCT(I) .GT. TCTMIN) GO TO 3760
          IF (TCT(I) .LE. TCTMM) GO TO 3760
            NMB(J) = I
            TCTMIN = TCT(I)
 3760     CONTINUE
            TCTMM = TCTMIN
 3770     CONTINUE
C
            MPGE = NREQ/6
            MXTRA = NREQ-6*MPGE
          IF (MPGE .EQ. 0) GO TO 4520
            II = 6
C
          DO 4510 ML = 1, MPGE
            MM = 1+6*(ML-1)
            MMF = 6+6*(ML-1)
            IM = 73
 3780       IZ = NREQ
            MCA = NREQ+1
            KTY = NREQ+6
          DO 3790 I = MCA, KTY
          DO 3790 K = 3, 12
 3790       PLF(I, K) = 0.0
C
          DO 3800 I = MM, MMF
            IZ = IZ+1
            KZ = NMB(I)
            IP(IZ) = IP(KZ)
            IO(IZ) = IO(KZ)
            IR(IZ) = IR(KZ)
            MC(IZ) = MC(KZ)
            MS(IZ) = MS(KZ)
            TC(IZ) = TC(KZ)
            TSUB(IZ) = TSUB(KZ)
            STJ(IZ) = STJ(KZ)
            CSP(IZ) = CSP(KZ)
            CC(IZ) = CC(KZ)
            CSB(IZ) = CSB(KZ)
            CR(IZ) = CR(KZ)
            CJ(IZ) = CJ(KZ)
            CTB(IZ) = CTB(KZ)
            CI(IZ) = CI(KZ)
            CO(IZ) = CO(KZ)
            CT(IZ) = CT(KZ)
            CM(IZ) = CM(KZ)
            CSR(IZ) = CSR(KZ)
            CSEAL(IZ) = CSEAL(KZ)
            CA(IZ) = CA(KZ)
            TCT(IZ) = TCT(KZ)
            JNR(IZ) = JNR(KZ)
            MLR(IZ) = MLR(KZ)
            JMR(IZ) = JMR(KZ)
            MTR(IZ) = MTR(KZ)
            MTB(IZ) = MTB(KZ)
            JPR(IZ) = JPR(KZ)
            NPL = NPP(KZ)+1
            NPP(IZ) = NPP(KZ)
            PLF(IZ, 13) = PLF(KZ, 13)
          DO 3800 IKZ = 2, NPL
            TO(IZ, IKZ) = TO(KZ, IKZ)
            PLF(IZ, IKZ) = PLF(KZ, IKZ)
```

```
 3800      CONTINUE
C
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,3810) (MX, MX = MM, MMF)
 3810 FORMAT  (//21X,*SUMMARY OF DESIGNS IN INCREASING ORDER OF TOTAL *
     1         *COST* // 12X *DESIGN NUMBER* 12X, 6I8 )
      WRITE (6,3820) (STAR, MX = 1, IM)
 3820 FORMAT  (12X,73A1)
           DO 3830 I = 1, II
                INP = IP(NREQ+I)
                PVNAM(I) = PVID(INP)
                INO = IO(NREQ+I)
                OVNAM(I) = OVID(INO)
                INR = IR(NREQ+I)
 3830           RNFNAM(I) = RNFID(INR)
      WRITE (6,3840) (PVNAM(I), I = 1, II)
 3840 FORMAT  (12X,*PAVEMENT TYPE* 12X, 6(5X,A3))
      WRITE (6,3850) (OVNAM(I), I = 1, II)
 3850 FORMAT  (12X,*OVERLAY  TYPE*12X,6(4X,A4))
      WRITE (6,3860) (RNFNAM(I), I = 1, II)
 3860 FORMAT  (12X,*REINFORCEMENT TYPE* 7X,6(4X,A4) )
                IN = NREQ+1
                I6 = IN+II-1
      WRITE (6,3870) (MC(I), I = IN, I6)
 3870 FORMAT  (/12X,*CONCRETE TYPE* 12X, 6I8)
      WRITE (6,3880) (MS(I), I = IN, I6)
 3880 FORMAT  (12X,*SUBBASE  TYPE* 12X, 6I8 )
      WRITE (6,3820) (STAR, I3 = 1, IM)
      WRITE (6,3890) (TC(I), I = IN, I6)
 3890 FORMAT  (/12X,*SLAB THICKNESS* 11X, 6F8.2)
      WRITE (6,3900) (TSUB(I), I = IN, I6)
 3900 FORMAT  (12X,*SUBBASE THICKNESS* 8X, 6F8.2  )
      WRITE (6,3910) (STJ(I), I = IN, I6)
 3910 FORMAT  (/ 12X,*SPACING TRANS. JOINTS* 4X, 6F8.2 )
      WRITE (6,3920) (WL, I = IN, I6)
 3920 FORMAT  (12X,*SPACING LONG. JOINTS* 5X, 6F8.2   )
      WRITE (6,3820) (STAR, I3 = 1, IM)
      WRITE (6,3990)
                LMAX = 0
           DO 3930 I = IN, I6
 3930      IF (NPP(I) .GT. LMAX) LMAX = NPP(I)
           IF (LMAX .EQ. 1) GO TO 3970
           DO 3960 J = 2, LMAX
                J1 = J-1
      WRITE (6,3940) J1
 3940 FORMAT  (12X,*OVERLAY THICKNESS* I2)
           DO 3950 I = IN, I6
                I1 = I-NREQ
                WHO(I1+2) = BLANK
                WHO(I1+3) = FIL
           IF (NPP(I) .LT. J) GO TO 3950
           IF (TO(I, J) .NE. 0.0) WRITE (6,WHO) (TO(I, J))
 3950      CONTINUE
 3960      CONTINUE
C
C          PERFORMANCE PERIODS
 3970 WRITE (6,3980) (PLF(I, 2), I = IN, I6)
 3980 FORMAT  (/12X,*INITIAL LIFE* 13X, 6F8.2 )
      WRITE (6,3990)
 3990 FORMAT  (10X)
                LMAX1 = LMAX+1
           DO 4020 J = 2, LMAX
                J2 = J-1
      WRITE (6,4000) J2
 4000 FORMAT  (12X,*OVERLAY PERF. LIFE* I2)
           DO 4010 I = IN, I6
                I1 = I-NREQ
                WHO(I1+2) = BLANK
                WHO(I1+3) = FIL
           IF (NPP(I) .LT. J) GO TO 4010
           IF (PLF(I, J+1) .NE. 0.0) WRITE (6,WHO) (PLF(I, J+1))
 4010      CONTINUE
 4020      CONTINUE
      WRITE (6,4030) (PLF(I, 13), I = IN, I6)
 4030 FORMAT  (/12X,*TOTAL PERFORMANCE LIFE*  3X, 6F8.2   )
C
      WRITE (6,3820) (STAR, I3 = 1, IM)
      WRITE (6,4040) (CSP(I), I = IN, I6)
 4040 FORMAT  (/ 12X, *COST OF SUBG. PREPARATION* 6F8.3 )
      WRITE (6,4050) (CC(I), I = IN, I6)
 4050 FORMAT  (12X,*COST OF CONCRETE* 9X, 6F8.3)
      WRITE (6,4060) (CSB(I), I = IN, I6)
 4060 FORMAT  (12X,*COST OF SUBBASE* 10X, 6F8.3)
      WRITE (6,4070) (CR(I), I = IN, I6)
 4070 FORMAT  (12X,*COST OF REINFORCEMENT* 4X, 6F8.3)
      WRITE (6,4080) (CJ(I), I = IN, I6)
 4080 FORMAT  (12X,*COST OF JOINTS* 11X, 6F8.3)
      WRITE (6,4090) (CTB(I), I = IN, I6)
 4090 FORMAT  (12X,*COST OF TIE BARS*  9X, 6F8.3    )
      WRITE (6,4100) (CI(I), I = IN, I6)
 4100 FORMAT  (/12X,*INITIAL CONST. COST* 6X, 6F8.3)
      WRITE (6,4110) (CO(I), I = IN, I6)
 4110 FORMAT  (12X,*OVERLAY CONST. COST* 6X, 6F8.3)
      WRITE (6,4120) (CT(I), I = IN, I6)
 4120 FORMAT  ( 12X,*TRAFFIC DELAY COST* 7X, 6F8.3)
      WRITE (6,4130) (CM(I), I = IN, I6)
 4130 FORMAT  (12X,*MAINTENANCE COST*    9X, 6F8.3)
      WRITE (6,4140) (CSR(I), I = IN, I6)
 4140 FORMAT  (12X,*SALVAGE RETURNS*    10X, 6F8.3)
           IF (NCS2 .EQ. 1) GO TO 4160
      WRITE (6,4150)
 4150 FORMAT  (12X,*SEAL COAT COST*)
           DO 4160 I = IN, I6
                I1 = I-NREQ
                WHO(I1+2) = BLANK
                WHO(I1+3) = GEO
           IF (OVNAM(I1) .NE. OVID(2)) WRITE (6,WHO) (CSEAL(I))
 4160      CONTINUE
           DO 4170 I = IN, I6
           IF (CA(I) .NE. 0.0) GO TO 4180
 4170      CONTINUE
           GO TO 4200
```

```
4180 WRITE (6,4190) (CA(I), I = IN, I6)
4190 FORMAT  (12X,*ANY ADDITIONAL COST * 5X, 6F8.3)
4200     CONTINUE
     WRITE (6,3990)
     WRITE (6,3820) (STAR, MX = 1, IM)
     WRITE (6,4210) (TCT(I), I = IN, I6)
4210 FORMAT  ( 12X,*TOTAL COST PER SQ YARD* 3X, 6F8.3)
     WRITE (6,3820) (STAR, MX = 1, IM)
C
C
         IF (PSN1 .NE. 0.0) GO TO 4510
     WRITE (6,1040) NPROB, TITLE
     WRITE (6,4220)
4220 FORMAT  (/ ,36X,*REINFORCEMENT DESIGN* /
    1        13X*DESIGN* 05X *REINFORCEMENT DESCRIPTION* 17X*MATERIAL*
    2         *  MATERIAL*/13X*NUMBER* 48X *NUMBER      NAME*/)
C
         DO 4420 IX = IN, I6
              JNRN = JNR(IX)
              MLRN = MLR(IX)
              JMRN = JMR(IX)
              MTRN = MTR(IX)
              MTBN = MTB(IX)
              JPRN = JPR(IX)
              MTRN4 = MTR(IX)-4
              MY = MM+IX-NREQ-1
              MU = NMB(MY)
         DO 4230 I = 1, JNRN
              RLN(IX, I) = RLN(MU, I)
4230          RLS(IX, I) = RLS(MU, I)
         DO 4240 I = 1, JMRN
              RTN(IX, I) = RTN(MU, I)
4240          RTS(IX, I) = RTS(MU, I)
         DO 4250 I = 1, JPRN
              TBN(IX, I) = TBN(MU, I)
4250          TBSP(IX, I) = TBSP(MU, I)
     WRITE (6,4260) MY
4260 FORMAT  (/14X,I2)
        IF (IR(IX) .EQ. 2) GO TO 4350
        IF (JNRN) 4280,4270
4270 WRITE (6,3410)
         GO TO 4320
4280 WRITE (6,4290) (RLN(IX, IY), IY = 1, JNRN)
     WRITE (6,4300) MLRN, (NAMEBS(MLRN, I), I = 1, 3)
     WRITE (6,4310) (RLS(IX, I), I = 1, JNRN)
4290 FORMAT  (1H+, 18X, *LONG. REINF.      BAR NO.* 4F6.0 )
4300 FORMAT  (1H+, 69X, I1, 4X, 2A4, A2 )
4310 FORMAT  ( 35X,                    *SPACING* 4F6.1 )
4320 WRITE (6,4330) (RTN(IX, I), I = 1, JMRN)
     WRITE (6,4300) MTRN4, (NAMEBS(MTRN, I), I = 1, 3)
     WRITE (6,4310) (RTS(IX, I), I = 1, JMRN)
     WRITE (6,4340) (RTN(IX, I), I = 1, JMRN)
     WRITE (6,4300) MTRN4, (NAMEBS(MTRN, I), I = 1, 3)
     WRITE (6,4310) (RTS(IX, I), I = 1, JMRN)
         GO TO 4420
4330 FORMAT  (19X *TRAN. REINF.      BAR NO.* 4F6.0 )
4340 FORMAT  (19X *TIE BARS      BAR NUMBER* 4F6.0 )
4350       IF (JNRN) 4370,4360
4360 WRITE (6,3460)
         GO TO 4400
4370 WRITE (6,4380) (RLS(IX, I), I = 1, JNRN)
     WRITE (6,4300) MLRN, (NAMEWS(MLRN, I), I = 1, 3)
     WRITE (6,4390) (RLN(IX, I), I = 1, JNRN)
4380 FORMAT  (1H+, 18X *LONG.REINF.MESH SPACING* 4F6.1 )
4390 FORMAT  (29X                 *MESH DIAMETER* 4F6.2 )
4400 WRITE (6,4410) (RTS(IX, I), I = 1, JMRN)
     WRITE (6,4300) MTRN, (NAMEWS(MTRN, I), I = 1, 3)
     WRITE (6,4390) (RTN(IX, I), I = 1, JMRN)
     WRITE (6,4340) (TBN(IX, I), I = 1, JPRN)
     WRITE (6,4300) MTBN, (NAMETS(MTBN, I), I = 1, 3)
     WRITE (6,4310) (TBSP(IX, I), I = 1, JPRN)
4410 FORMAT  (19X *TRAN.REINF.MESH SPACING* 4F6.1 )
4420     CONTINUE
C
C
             NNOSE = 0
     WRITE (6,4430)
4430 FORMAT  (//,13X, *DESIGN* 17X *SEAL COAT SCHEDULE*/ 13X*NUMBER* )
         DO 4490 I = IN, I6
         IF (IO(I) .GT. 1) GO TO 4490
             NNOSE = NNOSE+1
             MY = MM+I-NREQ-1
             NOSE = 0
             NPL = NPP(I)+1
         DO 4450 ISL = 3, NPL
             ISL1 = ISL-1
             PLIF = PLF(I, ISL)
         IF (PLIF .GT. AP) PLIF = AP
             TIME = PLIF-PLF(I, ISL1)
             SEAL = 0.0
4440         TISL = TFS+SEAL*TBS
         IF (TISL .GT. TIME) GO TO 4450
             NOSE = NOSE+1
             SCOT(NOSE) = PLF(I, ISL1)+TISL
             SEAL = SEAL+1.0
         GO TO 4440
4450     CONTINUE
         IF (NOSE .GT. 0) GO TO 4470
     WRITE (6,4460) MY
4460 FORMAT  ( 14X,I2,3X, *NO SEAL COAT IS FEASIBLE* )
         GO TO 4490
4470 WRITE (6,4480) MY, (SCOT(IS), IS = 1, NOSE)
4480 FORMAT  (14X,I2,03X,10F6.2)
4490     CONTINUE
         IF (NNOSE .EQ. 0) WRITE (6,4500)
4500 FORMAT  (19X,*SEAL COATS GENERALLY NOT PROVIDED ON THESE DESIGNS*)
4510     CONTINUE
C
C
         IF (MMF .EQ. NREQ) GO TO 4530
             MM = MM+6
             MMF = MM+MXTRA-1
```

```
      IF (MXTRA .EQ. 0) GO TO 4530
           I1 = MXTRA
           IM = 25+8*MXTRA
      GO TO 3780
4520       MM = 1
           MMF = MXTRA
           I1 = MMF
           IM = 25+8*MXTRA
      GO TO 3780
4530  CONTINUE
C
C
           NORTH = NOIN-KREJ
           KOIN = KSUB+KREJ
           KAP = NOIN-KOIN
           KFD = KLIF-KFUND
           JOIN = KFUND-KANAL
      WRITE (6,1030) NPROB, TITLE
      WRITE (6,4540) NOIN, KREJ, NORTH, KAP, KSUB, KLIFE, KLIF,
     1      KFD, KFUND, KANAL, JOIN
4540 FORMAT  ( 4(/), 33X, *INITIAL DESIGN ANALYSIS* //
     1     17X  *OUT OF A TOTAL OF*I4* INITIAL POSSIBLE DESIGNS,*/23X,I3
     2     * WERE REJECTED DUE TO MAX. INITIAL THICKNESS RESTRAINT* /
     3     17X  *OUT OF*I3* DESIGNS THUS LEFT,*/23X, I3, 1X,
     4     *DESIGNS WERE REJECTED SINCE THEY ARE OVERDESIGNS OF THE * /
     5     27X *INITIAL DESIGNS WHICH LAST THE ANALYSIS PERIOD* /17X
     6     *OUT OF*I3* DESIGNS THUS LEFT,* / 23X, I3
     7     * DESIGNS WERE REJECTED DUE  TO THEIR LIVES  BEING LESS */
     8     27X *THAN THE MINIMUM ALLOWABLE TIME  TO THE FIRST OVERLAY*/
     9     17X *OUT OF*    I3* DESIGNS THUS LEFT,*/ 23X, I3
     1     * DESIGNS WERE REJECTED DUE TO THE RESTRAINT OF MAXIMUM* /
     2     27X *INITIAL FUNDS AVAILABLE* / 17X,*OUT OF*,I3,* DESIGNS*
     3     * THUS LEFT,* /23X,I3,* DESIGNS WERE  ACCEPTABLE  INITIAL  *
     4     *DESIGNS WITH LIVES*/27X, *MORE THAN THE ANALYSIS PERIOD*/17X
     5     *AND THUS* 3X,I3,* DESIGNS WERE PASSED TO THE OVERLAY SUBSYST*
     6     *EM  TO * /32X *FORMULATE THE POSSIBLE OVERLAY STRATEGIES* )
      IF (JOIN .EQ. 0) GO TO 4650
      WRITE (6,4550) (I, I = 1, LM)
4550 FORMAT  ( 3(/), 32X *OVERLAY SUBSYSTEM ANALYSIS* // 10X,
     1       *DESIGN COMBINATION NUMBER*26X, 4I5 )
      WRITE (6,4560) (NTHT(I), I = 1, LM)
4560 FORMAT  (/10X*NUMBER WHEN MAX. OV. THICKNESS RESTRAINT WAS HIT   *
     1                  4I5)
      WRITE (6,4570) (NTMT(I), I = 1, LM)
4570 FORMAT  (10X*NUMBER WHEN MIN TIME BETWEEN OV RESTRAINT WAS HIT  *
     1                  4I5)
      WRITE (6,4580) (NOLT(I), I = 1, LM)
4580 FORMAT  (10X*NUMBER WHEN OVERLAYS NEEDED WERE MORE THAN EIGHT   *
     1                  4I5)
      WRITE (6,4590) (LFT(I), I = 1, LM)
4590 FORMAT  (10X*NUMBER OF TIMES  SUBROUTINE *1H**LIFF *1H**  WAS *
     1          * CALLED* 3X, 4I5 )
      WRITE (6,4600) (MANT(I), I = 1, LM)
4600 FORMAT  (10X*NUMBER OF TIMES  SUBROUTINE *1H**MANCE*1H**  WAS *
     1          * CALLED* 3X, 4I5 )
      WRITE (6,4610) (NTDCT(I), I = 1, LM)
4610 FORMAT  (10X*NUMBER OF TIMES  SUBROUTINE *1H** TDC *1H**  WAS *
     1          * CALLED* 3X, 4I5 )
      WRITE (6,4620) (NCNT(I), I = 1, LM)
4620 FORMAT  (10X*NUMBER OF  POSSIBLE OVERLAY STRATEGIES  OBTAINED    *
     1          4I5 )
      WRITE (6,4630) (NTOT(I), I = 1, LM)
4630 FORMAT  (/10X,*OUT OF A TOTAL OF * 33X, 4I5)
C
      WRITE (6,4640) NNT, NNR, NNC
4640 FORMAT  ( 3(/),21X*THUS FOR THE ENTIRE DESIGN SYSTEM * / 21X
     1          *OUT OF AN OVERALL TOTAL OF*I4*  OVERLAY STRATEGIES*/25X,
     2          I4* WERE REJECTED DUE TO DIFFERENT RESTRAINTS*/ 21X
     3          *AND *I4* WERE CONSIDERED FOR  OPTIMIZATION PROCESS* )
C
C
      GO TO 1000
4650  CONTINUE
C     ABOVE STATEMENT IS USED TO END THE PROGRAM
      END
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```
      SUBROUTINE LIFE (P1, BONE, D, T, SX, E, TUPTO)
C
      COMMON /LIFE/ P2, P2P, XJ, TOPKE, ITER, WTOT
      COMMON /ALL/ AP, ADTGR, ITYPE, RINT
C
C          LIFE FINDS THE TIME IN YEARS TO BRING A DESIGN FROM ITS
C                 INITIAL TO ITS TERMINAL SERVICEABILITY
C
C
C
                 BEST = 0.005
                 PEST = 0.005
                 TEST = 0.005
                 SAFETY = 0.9155
                 Z = E/TOPKE
                 C1 = AP*ADTGR/(AP*ADTGR+200.)
                 C2 = 200./(AP*ADTGR+200.)
                 WT = WTOT*(C1*(TUPTO/AP)**2+C2*TUPTO/AP)
                 QTOTAL = SQRT(5.-P2P)-SQRT(5.-P1)
                 PRO = 5.85-4.62*ALOG10(19.0)
                 XL = (Z*(D**3.0)/11.52)**0.25
                 RHOSP = (XJ*9000./D**2.)*(1.-7.15*SQRT(2.)/XL)
                 R18L = 1.010*ALOG10(RHOSP*690./SX)+ALOG10(0.301)
                 D1L = 1.995-0.517*R18L
                 D1 = 10.0**D1L
                 BETA = 1.+(3.63*19.0**5.20)/(D1)**8.46
                 F = SAFETY/BETA
                 CL = SAFETY*(7.35*D1L+PRO)
                 C = 10.**CL
C
                 DP = 0.10
                 DT = 1.00
                 TOPK = 100.0
                 YIT = 1.0
C
                 T = 0.0
                 ITER = 0
                 WTP = 0.0
C
                 P = P1
                 PP = P1
C
C
 100       IF (BONE .LT. BEST) GO TO 110
                 PP = PP-DP
                 P = P-DP
                 Q = SQRT(5.-PP)-SQRT(5.-P1)
                 RK = QTOTAL/(QTOTAL-Q)
                 TT = (1./BONE)*ALOG(RK)
                 DT = ABS(TT-T)
                 T = TT
           GO TO 120
 110             T = T+DT
                 PSC = 5.-(SQRT(5.-P1)+QTOTAL*(1.-EXP(-BONE*T)))**2
                 DP = PP-PSC
                 PP = PSC
                 P = P-DP
           IF (DP .EQ. 0.0) GO TO 130
 120             GT = (P1-P)/(P1-1.5)
                 WTPL = CL+F*ALOG10(GT)
                 WTP = 10.**WTPL
 130             TACT = T+TUPTO
                 WTT = WTOT*(C1*(TACT/AP)**2+C2*TACT/AP)
                 DW = WTT-WT
                 WT = WTT
                 WTP = WTP+DW
                 PM = P1-(P1-1.5)*(WTP/C)**(1./F)
                 ITER = ITER+1
           IF (PM .LT. P2) GO TO 140
                 P = PM
           IF (P .EQ. P2) GO TO 150
           GO TO 100
 140             P = P+DP
                 PP = PP+DP
                 T = T-DT
           IF (DT .LT. TEST .AND. DP .LT. PEST) GO TO 150
                 YIT = 0.0
                 DP = DP/2.
                 DT = DT/2.
                 WT = WTT-DW
                 WTP = WTP-DW
           GO TO 100
 150       CONTINUE
C
C          T        IS THE LIFE OF THE DESIGN
C                   THIS WILL BE TAKEN BACK TO THE MAIN PROGRAM
C
      RETURN
      END
```

```
      SUBROUTINE PUPY (XMEAN, SD, CL, X)
C
C          PUPY   MEANS PREDICT USING PROBABILITY
C          THIS SUBROUTINE DETERMINES THE DESIGNED VALUE OF CERTAIN
C          VARIABLE  DEPENDING UPON THE DISPERSION OF TEST RESULTS(SD)
C          OF THAT VARIABLE AND THE CONFIDENCE LEVEL REQUIRED FOR THE
C          DESIGN WITH RESPECT TO THAT VARIABLE
C
C
      DIMENSION Z(51)
C
      DATA (Z(I), I = 1,51 ) / 0.000,0.025,0.0503,0.07503,0.1005,0.1256,
     1       0.1510,0.1764,0.2017,0.2274,0.2533,0.2792,0.3055,0.3318,
     2       0.3584,0.3854,0.4124,0.4400,0.4678,0.4958,0.5244,0.5534,
     3       0.5829,0.6127,0.6433,0.6744,0.7062,0.7387,0.7721,0.8066,
     4       0.8415,0.8779,0.9154,0.9542,0.9946, 1.0365,1.0804,1.1264,
     5       1.1750,1.2263,1.2817,1.3406,1.4053,1.4757,1.5550,1.6450,
     6       1.7511,1.8814,2.0540,2.3267,3.900 /
C
C
C          XMEAN  IS THE MEAN VALUE OF THE VARIABLE
C          SD     IS THE STANDARD DEVIATION FOR THE VARIABLE
C          CL     IS THE CONFIDENCE LEVEL DESIRED FOR THE VARIABLE
C                 100 PERCENT MEANS NO RISK AT ALL. USE THE LOWEST VALUE
C
               AA = (50.-CL)/100.
               A = ABS(AA)
               XA = 100.*A
               NA = XA
               XNA = NA
               DA = XA-XNA
               XZ = Z(NA+1)+(Z(NA+2)-Z(NA+1))*DA
          IF (AA .LT. 0.00) XZ = -XZ
               X = XMEAN+XZ*SD
C
C          X      IS THE DESIGNED VALUE OF THE VARIABLE. THIS VALUE WILL
C                 BE TAKEN BACK TO THE MAIN PROGRAM
  300     CONTINUE
C
C
      RETURN
      END
```

```
      SUBROUTINE MANCE (PLP, PLF, TMPSY)
C
C          MANCE  MEANS MAINTENANCE
C
      COMMON /MANCE/ CERR, CLW, CMAT, DFTY
      COMMON /ALL/ AP, ADTGR, ITYPE, RINT
C
      REAL LAB, MAT, MTOT
C
C          DATA ARRAY FOR PERCENTAGE OF MAINTENANCE REQUIREMENTS
      DATA PLW,PERR,PMAT/0.60,0.19,0.21/
      DATA PLWR,PERRR,PMATR/0.44,0.21,0.35/
C
               T = PLF-PLP
          IF (PLF .GT. AP) T = AP-PLP
C
C          PLP    PERFORMANCE LIFE PREVIOUS
C          PLF    PERFORMANCE LIFE FOLLOWING
C          T - YEARS OF MAINTENANCE
C
          IF (ITYPE .EQ. 2) GO TO 400
               XLW = PLWR
               XERR = PERRR
               XMAT = PMATR
          GO TO 410
  400          XLW = PLW
               XERR = PERR
               XMAT = PMAT
  410     CONTINUE
C
               MTOT = 0.0
               NT = T+1.0
          DO 420 I = 1, NT
               XI1 = I-1
               YP = 19.72*(XI1)**2.+13.72*DFTY-183.0
          IF (YP .LE. 0.0) GO TO 420
               LAB = YP*XLW*CLW
               EQUIP = YP*XERR*CERR
               MAT = YP*XMAT*CMAT
               TOT = (LAB+EQUIP+MAT)/(1.+RINT/100.)**(XI1+PLP)
          IF (I .EQ. NT) GO TO 430
               MTOT = MTOT+TOT
  420     CONTINUE
C
  430          T1 = NT
               FTOT = TOT*(T1-T)
               TOT = TOT-FTOT
               MTOT = MTOT+TOT
C          MTOT   TOTAL MAINTENANCE COST FOR T YRS AFTER APPLYING RINT
C
               TMPSY = MTOT/(1760.0*16.0)
C          TMPSY  TOTAL MAINTENANCE COST PER SQUARE YARD
C                 THIS WILL BE TAKEN BACK TO THE MAIN PROGRAM
C
C
      RETURN
      END
```

```
      SUBROUTINE TDC (PLAT, OVTH, TDCSY, HPSY)
C
C         TDC    MEANS TRAFFIC DELAY COST
C
      COMMON /TDC/ PAPH, HPDC, PVSO, PVSN, DEQO, DEQN, AAS, ASOD,
     1       ASND,MODEL, DTSO, DTSN, DDOZ, NOLO, NOLN, ADT
      COMMON /ALL/ AP, ADTGR, ITYPE, RINT
C
      DIMENSION CCSR(6,6), CCSU(6,6), CURS(6,2), COD(1,2), CAP(4,3)
C
C THE FOLLOWING ARE TABLES CONTAINING THE USER COSTS.
C
C
C  COST OF SLOWING DOWN IN A RURAL AREA IN TEXAS.
C
C    EXCESS COST ABOVE CONTINUING AT INITIAL SPEED
C    IT INCLUDES OPERATING AS WELL AS TIME COST OF SPEED CHANGE CYCLE
C    ** DOLLARS PER 1000 CYCLES **
      DATA CCSR/8.473,18.2,31.55,50.36,77.932,120.546,0.,9.413,21.491,
     1       39.609,66.233,106.979,2*0.,11.354,28.422,53.917,92.482,3
     2       *0., 15.795,39.941,76.022,4*0.,22.612,56.405,5*0.,32.485/
C
C  COST OF SLOWING DOWN IN AN URBAN AREA
      DATA CCSU/5.869, 11.769, 19.5, 30.03, 45.002, 67.868, 0.,
     1       5.602, 12.857, 22.933, 37.338, 58.992, 2*0., 6.501,
     2       15.976, 29.61, 49.114, 3*0., 8.607, 21.448, 40.242,
     3       4*0., 11.856, 29.36, 5*0., 16.432/
C
C  COST OF OPERATING AT A UNIFORM SPEED IN TEXAS
C    DIFFERANCE OF TWO VALUES GIVES THE EXCESS COST OF OPERATING AT
C    REDUCED SPEED
C    IT INCLUDES OPERATING AS WELL AS TIME COST
C    ** DOLLARS PER 1000 VEHICLE MILES **
      DATA CURS/393.47, 214.53, 156.05, 129.03, 115.51,110.16, 362.43,
     1       197.06, 142.57, 116.84, 103.24, 96.73/
C
C  COST OF IDLING
C    IT INCLUDES OPERATING AS WELL TIME COST
C    ** DOLLARS PER 1000 VEHICLE HOURS **
      DATA COD/3499.76,3263.11/
C
C  CAPACITY TABLE
C    OUTPUT AND RECOVERY RATES, VEHICLES PER HOUR IN ONE DIRECTION
C    USED TO CALCULATE PO1, PN1, DO1, AND DN1 FOR MODEL NOS 3,4 AND 5
      DATA CAP/1350.,3000.,1400.,3000.,2700.,4500.,2800.,4700.,
     1       4350.,6200.,4500.,6400./
C
C
              ADTT = ADT*(1.0+ADTGR/100.0*PLAT)
C         HPSY   TOTAL TIME IN HOURS TO OVERLAY PER SQ. YD. OF PAVEMENT
C         OVTH   IS TOTAL OVERLAY THICKNESS DURING ONE OVERLAY
C
C
              LO = (ASOD+4.99)/10.0
              LN = (ASND+4.99)/10.0
              K = (AAS+5.0)/10.0
          IF (LO .GT. 6) LO = 6
          IF (LN .GT. 6) LN = 6
          IF (K .GT. 6) K = 6
C
               VPH = ADTT*PAPH/100.
C         VPH    TOTAL NUMBER OF VEHICLES PASSING THE OVERLAY AREA IN
C                ONE DIRECTION PER HOUR
C                SAME NUMBER OF VEHICLES ARE ASSUMED TO BE PASSING IN
C                THE OTHER DIRECTION ALSO
C  ****
C  MODEL NUMBER ONE
C  ****
C
               PO1 = 0.
               PN1 = 0.
               DO1 = 0.
               DN1 = 0.
C         ABOVE VALUES ARE BEING GIVEN FOR MODEL NUMBER ONE BUT THESE
C         VALUES ARE ALSO USED FOR OTHER MODELS IN CASE SEPERATE VALUES
C         OF THESE VARIABLES ARE NOT COMPUTED FOR THEM
C
               PO2 = PVSO/100.
               PN2 = PVSN/100.
               DO2 = DEQO
               DN2 = DEQN
               D = 1./12.
          GO TO (540,500,510,520,510), MODEL
C
C  ****
C  MODEL NUMBER TWO
C  ****
C
  500          A = DTSO/ASOD
               AQ = A*VPH
               PO1 = 0.5*(1.-EXP(-AQ))**2
               PN1 = PO1
               DO1 = (1.+EXP(2.*AQ))*(EXP(AQ)-AQ-1.)/(2.*VPH*PO1
     1                *(EXP(2.*AQ)-EXP(AQ)+1.))
               DN1 = DO1
          GO TO 540
C  ****
C  MODEL NUMBERS THREE AND FIVE
C  ****
C
  510          OUTRAT = CAP(2*ITYPE-1, NOLO)
               RECRAT = CAP(2*ITYPE, NOLO)
          IF (VPH .LE. OUTRAT) GO TO 540
               PO1 = HPDC*(VPH-OUTRAT)/(2.*VPH*D)
          IF (PO1 .GT. 1.) PO1 = 1.
               DO1 = HPDC*(VPH-OUTRAT)*(RECRAT-OUTRAT)/(2.*VPH*PO1
     1                *(RECRAT-VPH))
          GO TO 540
C  ****
C  MODEL NUMBER FOUR
C  ****
C
```

```
 520          OUTRAT = CAP(2*ITYPE-1, NOLO)
              RECRAT = CAP(2*ITYPE, NOLO)
         IF (VPH .LE. OUTRAT) GO TO 530
              PO1 = HPDC*(VPH-OUTRAT)/(2.*VPH*D)
         IF (PO1 .GT. 1.) PO1 = 1.
              DO1 = HPDC*(VPH-OUTRAT)*(RECRAT-OUTRAT)/(2.*VPH*PO1
     1             *(RECRAT-VPH))
 530          OUTRAT = CAP(2*ITYPE-1, NOLN)
              RECRAT = CAP(2*ITYPE, NOLN)
         IF (VPH .LE. OUTRAT) GO TO 540
              PN1 = HPDC*(VPH-OUTRAT)/(2.*VPH*D)
         IF (PN1 .GT. 1.) PN1 = 1.
              DN1 = HPDC*(VPH-OUTRAT)*(RECRAT-OUTRAT)/(2.*VPH*PN1
     1             *(RECRAT-VPH))
         GO TO 540
 540     CONTINUE
C
C  START COLLECTING ALL PERTINENT INFORMATION ABOUT DIFFERENT TYPES OF
C  DELAY COSTS.  THE FOLLOWING ARE THE DIFFERENT TYPES OF TRAFFIC DELAY
C  COSTS PER VEHICLE.
C
         GO TO (550,560), ITYPE
C  COST OF STOPPING FROM APPROACH SPEED IN A RURAL AREA.
 550          CO1 = CCSR(K, 1)/1000.
              CN1 = CO1
C COST OF SLOWING TO THRU SPEED IN A RURAL AREA.
              CO4 = CCSR(K, LO+1)/1000.
              CN4 = CCSR(K, LN+1)/1000.
         GO TO 570
C  COST OF STOPPING FROM APPROACH SPEED IN AN URBAN AREA.
 560          CO1 = CCSU(K, 1)/1000.
              CN1 = CO1
C COST OF SLOWING TO THRU SPEED IN AN URBAN AREA.
              CO4 = CCSU(K, LO+1)/1000.
              CN4 = CCSU(K, LN+1)/1000.
C COST OF DELAY DUE TO CONGESTION OUTSIDE THE RESTRICTED AREA.
 570          CO2 = DO1*COD(1, ITYPE)/1000.
              CN2 = DN1*COD(1, ITYPE)/1000.
C COST OF DRIVING AT A REDUCED SPEED.
         IF (MODEL .EQ. 5) GO TO 580
              CO3 = (CURS(LO, ITYPE)-CURS(K, ITYPE))*DTSO/1000.
              CN3 = (CURS(LN, ITYPE)-CURS(K, ITYPE))*DTSN/1000.
         GO TO 590
 580          CO3 = (CURS(LO, ITYPE)*DDOZ-CURS(K, ITYPE)*DTSO)
     1             /1000.
              CN3 = (CURS(LN, ITYPE)-CURS(K, ITYPE))*DTSN/1000.
C EXCESS COST OF STOPPING FROM THRU SPEED + COST OF IDLE TIME.ALL
C WITHIN THE RESTRICTED AREA.
 590     GO TO (600,610), ITYPE
 600          CO5 = CCSR(LO, 1)/1000.+DO2*COD(1, ITYPE)/1000.
              CN5 = CCSR(LN, 1)/1000.+DN2*COD(1, ITYPE)/1000.
         GO TO 620
 610          CO5 = CCSU(LO, 1)/1000.+DO2*COD(1, ITYPE)/1000.
              CN5 = CCSU(LN, 1)/1000.+DN2*COD(1, ITYPE)/1000.
C
C
C  START TOTAL COST COMPUTATIONS
C
 620          DCH = VPH*(PO1*(CO1+CO2+CO3)+(1.-PO1)*(CO3+CO4)+PO2
     1             *CO5)+VPH*(PN1*(CN1+CN2+CN3)+(1.-PN1)*(CN3+CN4)
     2             +PN2*CN5)
C
C        DCH IS TOTAL TRAFFIC DELAY COST PER HOUR OF OVERLAY CONSTR.
C
              DCSY = HPSY*DCH
C
              IPLAT = PLAT+0.5
              TDCSY = DCSY/(1.+RINT/100.)**PLAT
C        TDCSY  IS THE PRESENT WORTH OF TOTAL TRAFFIC DELAY COST PER
C               SQUARE YARD DURING OVERLAY CONSTRUCTION
C               THIS WILL BE TAKEN BACK TO THE MAIN PROGRAM
C
C
      RETURN
      END
```

APPENDIX 4

INPUT DATA LISTING FOR SAMPLE PROBLEM

```
RRR         RIGID PAVEMENT SYSTEM    AVERAGE PROBLEM
        0         0         0             0        0
       28      0000      3000        1      5418
               3000      6999        1      3359
               7000      7999        1      2005
               8000     11999        1      1633
              12000     15999        1       415
              16000     18000        1        71
              18001     18500        1       102
              18501     20000        1        31
              20001     21999        1        11
              22000     23999        1         4
              24000     25999        1         1
              26000     29999        1         1
               0000      6000        2       268
               6000     11999        2      4751
              12000     17999        2      2521
              18000     23999        2      1302
              24000     29999        2       306
              30000     32000        2        51
              32001     32500        2        43
              32501     33999        2        24
              34000     35999        2        17
              36000     37999        2        11
              38000     39999        2         7
              40000     41999        2         4
              42000     43999        2         3
              44000     45999        2         2
              46000     49999        2         1
              50000     54999        2         0
      5.0       5.0                 50.0      60.0               10000.0
     6.25      24.0       5.0        6.0  9.0  2.0 24.0   5.0       20.0
     4.20       2.5       4.0        1.5      0.06
      0.5       0.5       0.0        6.0       8.0    1    2                   1
      5.0       5.0       0.1        0.1      50.0      30.0       40.0        3
   2  7 2  450    40   95   140 2000000.0    195.0     700.0       12.0    400.0
      7 2  650    60   95   150 5500000.0    280.0    1000.0       14.0    300.0
                6.0      12.0        1.0
     100.      15.0      95.0                               1.0  3.0    1350.0
   2  GRANULAR          1.  1.5       20000.      400.0       2.0   6.  10.   2.
      C.TREATED         0.  3.0      900000.      600.0       3.0   5.  12.   2.
A-615,GR7570000 0.11      A-43260000 0.10
  A-15 STR33000 0.07  A-15 1NT40000 0.08
ASTM,A-4967000O 0.10
A-615,GR4040000 0.08 A-15   STR33000 0.07
   3    4    5          4   12     5   14    6   16              3    4
   1000.0      11.0    200000        100                240        0.90
      5.0       5.0    1100.0
      1.4       0.3                   15       100                    0
     10.0       2.0       2.3        1.0       5.0      50.0       12.0        4
```

APPENDIX 5

SAMPLE COMPUTER OUTPUT FOR PROGRAM RPS1

TRAFFIC INPUT

LOAD RANGE	AVG. LOAD IN KIPS	AXLE CODE	NO. OF AXLE APPLICATIONS
0 - 3000	1.500	SINGLE	5418
3000 - 6999	4.999	SINGLE	3359
7000 - 7999	7.499	SINGLE	2005
8000 - 11999	9.999	SINGLE	1633
12000 - 15999	14.000	SINGLE	415
16000 - 18000	17.000	SINGLE	71
18001 - 18500	18.250	SINGLE	102
18501 - 20000	19.250	SINGLE	31
20001 - 21999	21.000	SINGLE	11
22000 - 23999	23.000	SINGLE	4
24000 - 25999	25.000	SINGLE	1
26000 - 29999	28.000	SINGLE	1
0 - 6000	3.000	TANDEM	268
6000 - 11999	8.999	TANDEM	4751
12000 - 17999	15.000	TANDEM	2521
18000 - 23999	21.000	TANDEM	1302
24000 - 29999	27.000	TANDEM	306
30000 - 32000	31.000	TANDEM	51
32001 - 32500	32.250	TANDEM	43
32501 - 33999	33.250	TANDEM	24
34000 - 35999	34.999	TANDEM	17
36000 - 37999	36.999	TANDEM	11
38000 - 39999	38.999	TANDEM	7
40000 - 41999	40.999	TANDEM	4
42000 - 43999	42.999	TANDEM	3
44000 - 45999	44.999	TANDEM	2
46000 - 49999	47.999	TANDEM	1
50000 - 54999	52.499	TANDEM	0

TRAFFIC GROWTH AND DISTRIBUTION

AXLE GROWTH FACTOR	5.00
ADT GROWTH RATE	5.00
DIRECTIONAL DISTRIBUTION FACTOR	50.00
LANE DISTRIBUTION FACTOR	60.00
INITIAL AVERAGE DAILY TRAFFIC	10000.0

PROGRAM CONTROLS

DESIGNER SPECIFIES

BOTH CRCP AND JCP PAVEMENTS TO BE TRIED
BOTH CC AND AC OVERLAYS TO BE TRIED
BOTH DEFORMED BAR AND WIRE MESH REINFORCEMENT TO BE TRIED
PRINT LONG FORM OF OUTPUT
PRINT FIRST 12 DESIGNS IN INCREASING ORDER OF TOTAL COST

DESIGNERS DECISIONS OR RESTRAINTS

MAXIMUM INITIAL FUNDS AVAILABLE (DOLLARS)	6.25
MAX INITIAL THICKNESS, SLAB PLUS SUBBASE (INCHES)	24.00
MIN TIME TO FIRST OVERLAY (YEARS)	5.00
MIN TIME BETWEEN OVERLAYS (YEARS)	6.00
MAX TOTAL AC OVERLAY THICKNESS (INCHES)	9.00
MIN AC OVERLAY THICKNESS AT ONE TIME (INCHES)	2.00
MAX TOTAL CONC OVERLAY THICKNESS (INCHES)	24.00
MIN CONC OVERLAY THICKNESS AT ONE TIME (INCHES)	5.00
LENGTH OF ANALYSIS PERIOD (YEARS)	20.00

PERFORMANCE VARIABLES

INITIAL SERVICEABILITY INDEX	4.20
TERMINAL SERVICEABILITY INDEX	2.50
SERVICEABILITY INDEX AFTER AN OVERLAY	4.00
LOWER BOUND ON SERV. INDEX, NO TRAFFIC, INFINITE TIME	1.50
SWELLING CLAY PARAMETER, BONE	[illegible]

TRAFFIC DELAY COST VARIABLES

DISTANCE OVER WHICH TRAFFIC IS SLOWED,	OV. DIRECTION	.50
	N.OV. DIRECTION	.50
NO. OF OPEN LANES IN RESTRICTED ZONE,	OV. DIRECTION	1
	N.OV. DIRECTION	2
PERCENT VEHICLES STOPPED BY ROAD EQUIP,	OV. DIRECTION	5.00
	N.OV. DIRECTION	5.00
AVG DELAY CAUSED BY ROAD EQUIP (HOURS),	OV. DIRECTION	.10
	N.OV. DIRECTION	.10
AVG SPEED THROUGH OVERLAY ZONE (MPH),	OV. DIRECTION	[illegible]
	N.OV. DIRECTION	40.00
AVERAGE APPROACH SPEED TO OVERLAY AREA		[illegible]
DETOUR DISTANCE AROUND OVERLAY ZONE		[illegible]
ADT ARRIVING EACH HOUR OF CONSTRUCTION		[illegible]
NO. OF HOURS/DAY OVERLAY CONSTRUCTION OCCURS		[illegible]
TRAFFIC MODEL USED IN THE ANALYSIS		3
ROAD LOCATION		RURAL

```
RIGID   PAVEMENT   SYSTEM   RAMESH KHER        JULY 1970
PROB    RR         RIGID PAVEMENT SYSTEM   AVERAGE PROBLEM


                 MATERIALS (CONCRETE)

CONCRETE MIX DESIGN NUMBER              1          2
AGE OF TESTING CONCRETE                 7          7
MEASURING POINT                     THIRD      THIRD
FLEXURAL STRENGTH-MEAN VALUE       450.00     650.00
FLEXURAL STRENGTH-STD. DEV.         40.00      60.00
FLEX.STR.DESIGN CONF.LEVEL          95.00      95.00
TENSILE STRENGTH                   195.00     280.00
ELASTIC MODULUS                   2000000    5500000
WEIGHT                             140.00     150.00
CONSTRUCTION EQUIPMENT COST        700.00    1000.00
COST PER CUBIC YARD                 17.00      14.00
COST OF SURFACING CONCRETE         400.00     300.00

      MINIMUM ALLOWABLE CONCRETE THICKNESS              6.00
      MAXIMUM ALLOWABLE CONCRETE THICKNESS             12.00
      PRACTICAL INCREMENT FOR POURING CONCRETE          1.00

                 MATERIALS (STEEL)

                                          1          2
BARS
    LONGITUDINAL
      BAR STEEL ASTM DESIG   A-615,GR75      A-432
      TENSILE YIELD PT STR    70000.00    60000.00
      COST/LB OF BAR STEEL        .110        .100
    TRANSVERSE
      BAR STEEL ASTM DESIG    A-15 STR    A-15 INT
      TENSILE YIELD PT STR    33000.00    40000.00
      COST/LB OF BAR STEEL        .070        .080
    BAR NOS. TO BE TRIED             3           4           5

WIRE MESHES
      WIRE MESH ASTM DESIG   ASTM,A-496
      TENSILE YIELD PT STR    70000.00
      COST/LB OF WIRE MESH        .100
    MESH SIZES TO BE TRIED
     LONG. WIRE SPACING          4.00        5.00        6.00
     TRAN. WIRE SPACING         12.00       14.00       16.00

TIE BARS USED WITH W. MESH
      TIE BAR ASTM  DESIG.   A-615,GR40   A-15  STR
      TENSILE YIELD PT STR    40000.00    33000.00
      COST /LB OF TIE BARS        .080        .070
    TIE BAR NOS TO BE TRIED          3           4
```

```
RIGID   PAVEMENT   SYSTEM   RAMESH KHER        JULY 1970
PROB    RR         RIGID PAVEMENT SYSTEM   AVERAGE PROBLEM

                 MATERIALS (SUBGRADE)

     SUBGRADE K MEAN VALUE                                        100.00
     SUBGRADE K VALUE, STANDARD DEVIATION                          15.00
     SUBGRADE K VALUE, DESIGN CONFIDENCE LEVEL                     95.00
     SUBGRADE FRICTION FACTOR                                       1.00
     SUBGRADE ERODABILITY FACTOR                                    3.00
     COST PER LANE MILE OF SUBGRADE PREPARATION                  1350.00

                 MATERIALS (SUBBASE)

     SUBBASE TYPE            GRANULAR C.TREATED
     ERODABILITY FACTOR          1.00      0.00
     FRICTION FACTOR             1.50      3.00
     ELASTIC MODULUS            20000    900000
     CONSTR EQUIPMENT COST     400.00    600.00
     COST/ COMPACTED CU YD       2.00      3.00
     MIN ALLOWED THICKNESS       6.00      6.00
     MAX ALLOWED THICKNESS      10.00     12.00
     INCREMENT FOR SUBBASE       2.00      2.00

                      OVERLAY

     INITIAL COST PER LANE MILE OF EQUIPMENT FOR OVERLAYS        1000.00
     COST/CU YD OF IN PLACE COMPACTED ASPHALT CONCRETE             11.00
     ASPHALT CONCRETE MODULUS VALUE                               200000
     PRODUCTION RATE OF COMPACTED ASPHALT CONCRETE                100.00
     CONCRETE PRODUCTION RATE                                     240.00
     CONCRETE COEFFICIENT                                            .90

                      SEAL COATS

     TIME TO FIRST SEAL COAT AFTER AC OVERLAY                       5.00
     TIME BETWEEN SEAL COATS                                        5.00
     COST PER LANE MILE OF A SEAL COAT                           1100.00

                      JOINTS

     COST/FT OF TRANS. JOINT (SAWING, DOWELS AND/OR SEALING)        1.40
     COST/FT OF LONG. JOINT (SEALING)                                .30
     RANGE OF SPACING FOR CONTRACTION JOINTS, LOWER VALUE          15.00
                                              UPPER VALUE         100.00
     NO OF TRANS. CONST. OR WARPING JOINTS/MILE FOR CRCP               0

            MAINTENANCE, DIMENSIONS AND MISCELLANEOUS

     DAYS OF FREEZING TEMPERATURE PER YEAR                          1-.00
     COMPOSITE LABOR WAGE FOR MAINTENANCE OPERATIONS                2-.-
     COMPOSITE EQUIPMENT RENTAL RATE FOR MAINT OPERATIONS           2.30
     COST OF MATERIALS FOR MAINTENANCE OPERATIONS                   1.00
     SALVAGE PERCENT AT THE END OF ANALYSIS PERIOD                 5-.-
     WIDTH OF EACH LANE                                            12.00
     TOTAL NUMBER OF LANES IN BOTH DIRECTIONS                          4
     RATE OF INTEREST OR TIME VALUE OF MONEY                        5.00
```

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB HR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

MOST ECONOMICAL JCP PAVEMENT DESIGN WITH AC OVERLAY

INITIAL CONSTRUCTION, LIFE IS 6.465 YEARS

MATERIALS					DESCRIPTION MATERIAL NUMBER	MATERIAL NAME
CONCRETE	9.00 INCHES				2	
SUBBASE	6.00 INCHES				1	
LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
	MESH DIAMETER	.19	.22	.24		
TRAN.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
	MESH DIAMETER	.22	.24	.26		
TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
	SPACING	19.6	34.9			

TRANSVERSE JOINT SPACING 55 FEET
LONGITUDINAL JOINT SPACING 12 FEET

SUBSEQUENT CONSTRUCTION
1 OVERLAY WITH 2.00 INCHES OF AC AFTER 6.465 YEARS
2 OVERLAY WITH 2.00 INCHES OF AC AFTER 13.571 YEARS

TOTAL OVERLAY THICKNESS 4.00 INCHES TOTAL LIFE 21.819 YEARS

COST ANALYSIS DOLLARS PER SQUARE YARD	
INITIAL CONSTRUCTION	
COST OF SUBGRADE PREPARATION	.192
COST OF CONCRETE	3.685
COST OF SUBBASE	.390
COST OF REINFORCEMENT	.389
COST OF JOINTS	.342
COST OF TIE BARS	.013
TOTAL INITIAL CONSTRUCTION COST	5.010
TOTAL OVERLAY CONSTRUCTION COST	.938
TOTAL T.D. COST DURING OV. CONSTRUCTION	.079
TOTAL MAINTENANCE COST	.144
TOTAL SEAL COAT COST AFTER OV. CONSTRUCTION	.152
SALVAGE RETURNS	-.890
TOTAL OVERALL COST	5.432

DESIGN ANALYSIS
TOTAL 98 INITIAL DESIGNS WERE EXAMINED, OUT OF WHICH,
58 DESIGNS WERE REJECTED DUE TO USER RESTRAINTS
40 REMAINING INITIAL DESIGNS PRODUCED 281 OVERLAY STRATEGIES

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB HR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

MOST ECONOMICAL JCP PAVEMENT DESIGN WITH CC OVERLAY

INITIAL CONSTRUCTION, LIFE IS 9.342 YEARS

MATERIALS					DESCRIPTION MATERIAL NUMBER	MATERIAL NAME
CONCRETE	12.00 INCHES				1	
SUBBASE	6.00 INCHES				1	
LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
	MESH DIAMETER	.20	.22	.24		
TRAN.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
	MESH DIAMETER	.25	.27	.29		
TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
	SPACING	15.8	28.0			

TRANSVERSE JOINT SPACING 45 FEET
LONGITUDINAL JOINT SPACING 12 FEET

SUBSEQUENT CONSTRUCTION
1 OVERLAY WITH 5.00 INCHES OF CC AFTER 9.342 YEARS

TOTAL OVERLAY THICKNESS 5.00 INCHES TOTAL LIFE 23.579 YEARS

COST ANALYSIS DOLLARS PER SQUARE YARD	
INITIAL CONSTRUCTION	
COST OF SUBGRADE PREPARATION	.192
COST OF CONCRETE	4.156
COST OF SUBBASE	.390
COST OF REINFORCEMENT	.423
COST OF JOINTS	.392
COST OF TIE BARS	.016
TOTAL INITIAL CONSTRUCTION COST	5.569
TOTAL OVERLAY CONSTRUCTION COST	1.156
TOTAL T.D. COST DURING OV. CONSTRUCTION	.042
TOTAL MAINTENANCE COST	.357
SALVAGE RETURNS	-1.068
TOTAL OVERALL COST	6.055

DESIGN ANALYSIS
TOTAL 98 INITIAL DESIGNS WERE EXAMINED, OUT OF WHICH,
58 DESIGNS WERE REJECTED DUE TO USER RESTRAINTS
40 REMAINING INITIAL DESIGNS PRODUCED 91 OVERLAY STRATEGIES

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB AR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

SUMMARY OF DESIGNS IN INCREASING ORDER OF TOTAL COST

DESIGN NUMBER	1	2	3	4	5	6
PAVEMENT TYPE	JCP	CRC	CRC	CRC	CRC	JCP
OVERLAY TYPE	AC	AC	AC	AC	AC	AC
REINFORCEMENT TYPE	MESH	MESH	MESH	MESH	BARS	MESH
CONCRETE TYPE	2	2	2	2	1	2
SUBBASE TYPE	1	2	2	2	2	1
SLAB THICKNESS	9.00	6.00	6.00	7.00	7.00	9.00
SUBBASE THICKNESS	6.00	8.00	10.00	6.00	8.00	6.00
OVERLAY THICKNESS 1	2.00	2.50	2.00	2.00	2.00	2.50
OVERLAY THICKNESS 2	2.00	2.00	2.00	2.00	2.00	2.00
INITIAL LIFE	6.47	5.02	5.45	7.72	5.84	6.47
OVERLAY PERF. LIFE 1	13.57	11.37	11.99	16.63	12.32	13.90
OVERLAY PERF. LIFE 2	21.82	20.04	20.90	27.94	20.40	22.64
TOTAL PERFORMANCE LIFE	21.82	20.04	20.90	27.94	20.40	22.64
SPACING TRANS. JOINTS	55.00	.00	.00	.00	.00	55.00
SPACING LONG. JOINTS	12.00	12.00	12.00	12.00	12.00	12.00
COST OF SUBG. PREPARATION	.192	.192	.192	.192	.192	.192
COST OF CONCRETE	3.685	2.518	2.518	2.907	2.490	3.685
COST OF SUBBASE	.390	.752	.919	.585	.752	.390
COST OF REINFORCEMENT	.389	1.039	1.039	1.213	1.269	.389
COST OF JOINTS	.342	.112	.112	.112	.112	.342
COST OF TIE BARS	.013	.017	.017	.020	.019	.013
INITIAL CONST. COST	5.010	4.631	4.798	5.029	4.834	5.010
OVERLAY CONST. COST	.938	1.142	.997	.851	.979	1.043
TRAFFIC DELAY COST	.079	.091	.080	.076	.080	.089
MAINTENANCE COST	.144	.148	.141	.213	.139	.148
SALVAGE RETURNS	-.890	-.699	-.670	-.743	-.670	-.919
SEAL COAT COST	.152	.166	.162	.094	.159	.151
TOTAL COST PER SQ YARD	5.432	5.479	5.508	5.510	5.521	5.522

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB AR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

REINFORCEMENT DESIGN

DESIGN NUMBER	REINFORCEMENT DESCRIPTION					MATERIAL NUMBER	MATERIAL NAME
1	LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
		MESH DIAMETER	.19	.22	.24		
	TRANS.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
		MESH DIAMETER	.22	.24	.26		
	TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
		SPACING	19.6	34.9			
2	LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
		MESH DIAMETER	.35	.39	.43		
	TRANS.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
		MESH DIAMETER	.26	.28	.30		
	TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
		SPACING	14.7	26.2			
3	LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
		MESH DIAMETER	.35	.39	.43		
	TRANS.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
		MESH DIAMETER	.26	.28	.30		
	TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
		SPACING	14.7	26.2			
4	LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
		MESH DIAMETER	.38	.42	.46		
	TRANS.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
		MESH DIAMETER	.28	.30	.32		
	TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
		SPACING	12.6	22.4			
5	LONG. REINF.	BAR NO.	3	4		2	A-432
		SPACING	3.9	7.0			
	TRANS. REINF.	BAR NO.	3	4	5	2	A-15 INT
		SPACING	13.5	24.0	37.6		
	TIE BARS	BAR NUMBER	3	4	5	2	A-15 INT
		SPACING	13.5	24.0	37.6		
6	LONG.REINF.MESH	SPACING	4.0	5.0	6.0	1	ASTM,A-496
		MESH DIAMETER	.19	.22	.24		
	TRANS.REINF.MESH	SPACING	12.0	14.0	16.0	1	ASTM,A-496
		MESH DIAMETER	.22	.24	.26		
	TIE BARS	BAR NUMBER	3	4		1	A-615,GR40
		SPACING	19.6	34.9			

SEAL COAT SCHEDULE

DESIGN NUMBER		
1	11.47 16.57	
2	10.[illegible]	16.37
3	10.45	16.99
4	12.72	
5	10.[illegible]	17.32
6	11.47	1[illegible].91

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RIGID   PAVEMENT   SYSTEM    RAMESH KHER         JULY 1970
PROB   RR          RIGID PAVEMENT SYSTEM   AVERAGE PROBLEM

    MOST ECONOMICAL CRC PAVEMENT DESIGN WITH   AC OVERLAY

INITIAL CONSTRUCTION,    LIFE IS    5.016 YEARS

   MATERIALS
                                                          DESCRIPTION
                                                       MATERIAL    MATERIAL
                                                        NUMBER       NAME

   CONCRETE        6.00 INCHES                            2
   SUBBASE         8.00 INCHES                            2
   LONG.REINF.MESH SPACING    4.0    5.0    6.0           1       ASTM,A-496
             MESH DIAMETER    .35    .39    .43
   TRAN.REINF.MESH SPACING   12.0   14.0   16.0           1       ASTM,A-496
             MESH DIAMETER    .26    .28    .30
   TIE BARS      BAR NUMBER     3      4                  1       A-615,GR40
                    SPACING  14.7   26.2

              TRANSVERSE JOINT SPACING       0 FEET
              LONGITUDINAL JOINT SPACING    12 FEET


SUBSEQUENT CONSTRUCTION
   1  OVERLAY WITH  2.50 INCHES OF    AC AFTER    5.016 YEARS
   2  OVERLAY WITH  2.00 INCHES OF    AC AFTER   11.373 YEARS

     TOTAL OVERLAY THICKNESS    4.50 INCHES     TOTAL LIFE  20.038 YEARS


COST ANALYSIS    DOLLARS PER SQUARE YARD
     INITIAL CONSTRUCTION
        COST OF SUBGRADE PREPARATION                       .192
        COST OF CONCRETE                                  2.518
        COST OF SUBBASE                                    .752
        COST OF REINFORCEMENT                             1.039
        COST OF JOINTS                                     .112
        COST OF TIE BARS                                   .017

     TOTAL INITIAL CONSTRUCTION COST                      4.631
     TOTAL OVERLAY CONSTRUCTION COST                      1.142
     TOTAL T.D. COST DURING OV. CONSTRUCTION               .091
     TOTAL MAINTENANCE COST                                .148
     TOTAL SEAL COAT COST AFTER OV. CONSTRUCTION           .166
     SALVAGE RETURNS                                      -.699

    TOTAL OVERALL COST                                    5.479

DESIGN ANALYSIS
   TOTAL  98 INITIAL DESIGNS WERE EXAMINED, OUT OF WHICH,
          59 DESIGNS WERE REJECTED DUE TO USER RESTRAINTS
          39 REMAINING INITIAL DESIGNS PRODUCED  226 OVERLAY STRATEGIES
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RIGID   PAVEMENT   SYSTEM    RAMESH KHER         JULY 1970
PROB   RR          RIGID PAVEMENT SYSTEM   AVERAGE PROBLEM

    MOST ECONOMICAL CRC PAVEMENT DESIGN WITH   CC OVERLAY

INITIAL CONSTRUCTION,    LIFE IS    7.719 YEARS

   MATERIALS
                                                          DESCRIPTION
                                                       MATERIAL    MATERIAL
                                                        NUMBER       NAME

   CONCRETE        7.00 INCHES                            2
   SUBBASE         6.00 INCHES                            2
   LONG.REINF.MESH SPACING    4.0    5.0    6.0           1       ASTM,A-496
             MESH DIAMETER    .38    .42    .46
   TRAN.REINF.MESH SPACING   12.0   14.0   16.0           1       ASTM,A-496
             MESH DIAMETER    .28    .30    .32
   TIE BARS      BAR NUMBER     3      4                  1       A-615,GR40
                    SPACING  12.6   22.4

              TRANSVERSE JOINT SPACING       0 FEET
              LONGITUDINAL JOINT SPACING    12 FEET


SUBSEQUENT CONSTRUCTION
   1  OVERLAY WITH  5.00 INCHES OF    CC AFTER    7.719 YEARS

     TOTAL OVERLAY THICKNESS    5.00 INCHES     TOTAL LIFE  24.838 YEARS


COST ANALYSIS    DOLLARS PER SQUARE YARD
     INITIAL CONSTRUCTION
        COST OF SUBGRADE PREPARATION                       .192
        COST OF CONCRETE                                  2.907
        COST OF SUBBASE                                    .585
        COST OF REINFORCEMENT                             1.213
        COST OF JOINTS                                     .112
        COST OF TIE BARS                                   .020

     TOTAL INITIAL CONSTRUCTION COST                      5.029
     TOTAL OVERLAY CONSTRUCTION COST                      1.461
     TOTAL T.D. COST DURING OV. CONSTRUCTION               .042
     TOTAL MAINTENANCE COST                                .381
     SALVAGE RETURNS                                      -.879

    TOTAL OVERALL COST                                    6.034

DESIGN ANALYSIS
   TOTAL  98 INITIAL DESIGNS WERE EXAMINED, OUT OF WHICH,
          59 DESIGNS WERE REJECTED DUE TO USER RESTRAINTS
          39 REMAINING INITIAL DESIGNS PRODUCED   59 OVERLAY STRATEGIES
```

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB RR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

SUMMARY OF DESIGNS IN INCREASING ORDER OF TOTAL COST

DESIGN NUMBER	7	8	9	10	11	12
PAVEMENT TYPE	JCP	JCP	CRC	JCP	CRC	CRC
OVERLAY TYPE	AC	AC	AC	AC	AC	AC
REINFORCEMENT TYPE	MESH	MESH	MESH	MESH	MESH	BARS
CONCRETE TYPE	2	1	2	1	2	1
SUBBASE TYPE	1	1	2	1	2	2
SLAB THICKNESS	9.00	11.00	6.00	11.00	6.00	7.00
SUBBASE THICKNESS	8.00	6.00	8.00	6.00	10.00	8.00
OVERLAY THICKNESS 1	2.00	2.00	3.00	2.50	2.50	2.50
OVERLAY THICKNESS 2	2.00	2.00	2.00	2.00	2.00	2.00
INITIAL LIFE	6.53	7.18	5.02	7.18	5.45	5.86
OVERLAY PERF. LIFE 1	13.71	14.81	11.93	15.08	12.56	12.75
OVERLAY PERF. LIFE 2	22.03	23.25	21.40	23.91	22.32	21.43
TOTAL PERFORMANCE LIFE	22.03	23.25	21.40	23.91	22.32	21.43
SPACING TRANS. JOINTS	55.00	45.00	.00	45.00	.00	.00
SPACING LONG. JOINTS	12.00	12.00	12.00	12.00	12.00	12.00
COST OF SUBG. PREPARATION	.192	.192	.192	.192	.192	.192
COST OF CONCRETE	3.685	3.823	2.518	3.823	2.518	2.490
COST OF SUBBASE	.501	.390	.752	.390	.919	.752
COST OF REINFORCEMENT	.389	.387	1.039	.387	1.039	1.269
COST OF JOINTS	.342	.392	.112	.392	.112	.112
COST OF TIE BARS	.013	.015	.017	.015	.017	.019
INITIAL CONST. COST	5.121	5.199	4.631	5.199	4.798	4.834
OVERLAY CONST. COST	.933	.896	1.250	.999	1.102	1.086
TRAFFIC DELAY COST	.078	.077	.101	.087	.090	.090
MAINTENANCE COST	.145	.163	.144	.168	.141	.136
SALVAGE RETURNS	-.890	-.921	-.728	-.950	-.699	-.699
SEAL COAT COST	.152	.146	.164	.086	.160	.156
TOTAL COST PER SQ YARD	5.540	5.561	5.562	5.590	5.593	5.606

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB RR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

REINFORCEMENT DESIGN

DESIGN NUMBER	REINFORCEMENT DESCRIPTION					MATERIAL NUMBER	MATERIAL NAME
7	LONG.REINF.MESH SPACING		4.0	5.0	6.0	1	ASTM.A-496
		MESH DIAMETER	.19	.22	.24		
	TRAN.REINF.MESH SPACING		12.0	14.0	16.0	1	ASTM.A-496
		MESH DIAMETER	.22	.24	.26		
	TIE BARS	BAR NUMBER	3	4		1	A-615.GR40
		SPACING	19.6	34.9			
8	LONG.REINF.MESH SPACING		4.0	5.0	6.0	1	ASTM.A-496
		MESH DIAMETER	.19	.21	.23		
	TRAN.REINF.MESH SPACING		12.0	14.0	16.0	1	ASTM.A-496
		MESH DIAMETER	.24	.24	.27		
	TIE BARS	BAR NUMBER	3	4		1	A-615.GR40
		SPACING	17.2	30.6			
9	LONG.REINF.MESH SPACING		4.0	5.0	6.0	1	ASTM.A-496
		MESH DIAMETER	.35	.39	.43		
	TRAN.REINF.MESH SPACING		12.0	14.0	16.0	1	ASTM.A-496
		MESH DIAMETER	.26	.29	.30		
	TIE BARS	BAR NUMBER	3	4		1	A-615.GR40
		SPACING	14.7	26.2			
10	LONG.REINF.MESH SPACING		4.0	5.0	6.0	1	ASTM.A-496
		MESH DIAMETER	.19	.21	.23		
	TRAN.REINF.MESH SPACING		12.0	14.0	16.0	1	ASTM.A-496
		MESH DIAMETER	.24	.24	.27		
	TIE BARS	BAR NUMBER	3	4		1	A-615.GR40
		SPACING	17.2	30.6			
11	LONG.REINF.MESH SPACING		4.0	5.0	6.0	1	ASTM.A-496
		MESH DIAMETER	.35	.39	.43		
	TRAN.REINF.MESH SPACING		12.0	14.0	16.0	1	ASTM.A-496
		MESH DIAMETER	.26	.29	.30		
	TIE BARS	BAR NUMBER	3	4		1	A-615.GR40
		SPACING	14.7	26.2			
12	LONG. REINF.	BAR NO.	3	4		2	A-432
		SPACING	3.9	7.0			
	TRAN. REINF.	BAR NO.	3	4	5	2	A-15 INT
		SPACING	13.5	24.0	37.6		
	TIE BARS	BAR NUMBER	3	4	5	2	A-15 INT
		SPACING	13.5	24.0	37.6		

SEAL COAT SCHEDULE

DESIGN NUMBER		
7	11.53	18.71
8	12.18	19.81
9	10.02	14.93
10	12.18	
11	10.45	17.30
12	11.84	17.75

RIGID PAVEMENT SYSTEM RAMESH KHER JULY 1970
PROB RR RIGID PAVEMENT SYSTEM AVERAGE PROBLEM

INITIAL DESIGN ANALYSIS

OUT OF A TOTAL OF 196 INITIAL POSSIBLE DESIGNS,
0 WERE REJECTED DUE TO MAX. INITIAL THICKNESS RESTRAINT
OUT OF196 DESIGNS THUS LEFT,
0 DESIGNS WERE REJECTED SINCE THEY ARE OVERDESIGNS OF THE INITIAL DESIGNS WHICH LAST THE ANALYSIS PERIOD
OUT OF196 DESIGNS THUS LEFT,
56 DESIGNS WERE REJECTED DUE TO THEIR LIVES BEING LESS THAN THE MINIMUM ALLOWABLE TIME TO THE FIRST OVERLAY
OUT OF140 DESIGNS THUS LEFT,
61 DESIGNS WERE REJECTED DUE TO THE RESTRAINT OF MAXIMUM INITIAL FUNDS AVAILABLE
OUT OF 79 DESIGNS THUS LEFT,
0 DESIGNS WERE ACCEPTABLE INITIAL DESIGNS WITH LIVES MORE THAN THE ANALYSIS PERIOD
AND THUS 79 DESIGNS WERE PASSED TO THE OVERLAY SUBSYSTEM TO FORMULATE THE POSSIBLE OVERLAY STRATEGIES

OVERLAY SUBSYSTEM ANALYSIS

DESIGN COMBINATION NUMBER	1	2	3	4
NUMBER WHEN MAX. OV. THICKNESS RESTRAINT WAS HIT	48	0	30	0
NUMBER WHEN MIN TIME BETWEEN OV RESTRAINT WAS HIT	10	0	6	0
NUMBER WHEN OVERLAYS NEEDED WERE MORE THAN EIGHT	0	0	0	0
NUMBER OF TIMES SUBROUTINE *LIFE * WAS CALLED	580	142	449	79
NUMBER OF TIMES SUBROUTINE *MANCE* WAS CALLED	580	142	449	79
NUMBER OF TIMES SUBROUTINE * TOC * WAS CALLED	580	142	449	79
NUMBER OF POSSIBLE OVERLAY STRATEGIES OBTAINED	291	91	226	59
OUT OF A TOTAL OF	339	91	262	59

THUS FOR THE ENTIRE DESIGN SYSTEM
OUT OF AN OVERALL TOTAL OF 751 OVERLAY STRATEGIES
94 WERE REJECTED DUE TO DIFFERENT RESTRAINTS
AND 657 WERE CONSIDERED FOR OPTIMIZATION PROCESS

APPENDIX 6

DEVELOPMENT OF MATHEMATICAL MODELS

APPENDIX 6A. DEVELOPMENT OF MODELS FOR FOUNDATION STRENGTH

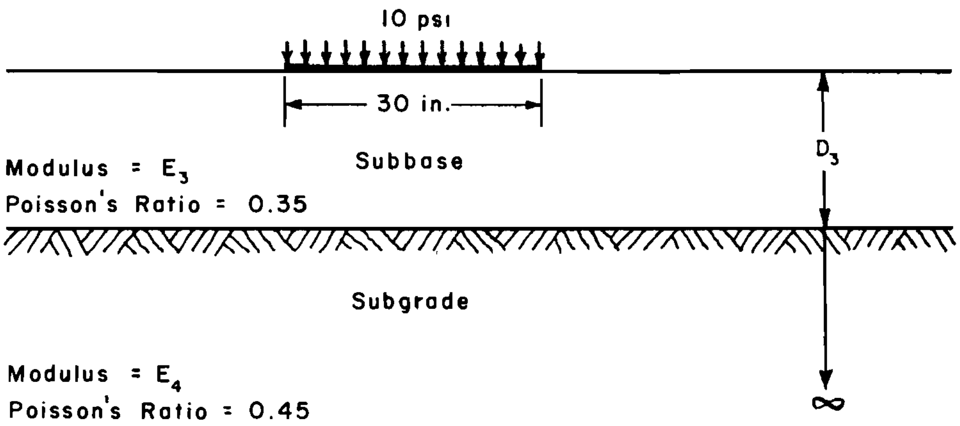
Layered elastic theory is used to compute the increase in the value of modulus of support due to a subbase. Figure 19 describes the two-layered system analyzed for developing this model. The system is loaded with 10 psi pressure applied uniformly over a 30-inch-diameter circular plate. The deflection at the bottom of the plate is computed using program LAYER, developed by Chevron Research Corporation. The Poisson's ratios of the subbase and the subgrade are held constant to reduce the dimensions of the analysis and also because their effects, relative to the variables which are being considered, are not significant.

A wide range of values for the subbase thickness and the modulus of subbase and the subgrade are adopted for the analysis. The table on Fig 19 shows the numerical values and the number of levels for each variable considered for analysis. The levels used for the variables are equally spaced to analyze the results using orthogonal polynomial regression analysis for developing the prediction equation.

The external pressure of 10 psi when divided by the maximum deflection computed under the plate gives the modulus value at the top of the subbase in terms of pounds per cubic inch.

The complete factorial comprised of 6 × 7 × 6 (=252) problems is analyzed and the k values at the top of the subbases are computed. Table 7 shows typical data for a 6-inch subbase.

A regression analysis was run to develop a prediction model for all levels of the three variables analyzed. It was found that a model of acceptable accuracy could not be obtained due to the wide range of response. Various transformations were tried for the variables and the response but it did not improve the results and, therefore, the decision was made to divide the data into three smaller factorials. These factorials were comprised of all the values of E_3 and E_4 and the values of subbase thicknesses at the following levels:



Levels of Variables for Subbase Analysis

Level Number	1	2	3	4	5	6	7
D_3 (in.)	0	3	6	9	12	15	18
Log E_3^*	4.0	4.35	4.70	5.05	5.40	5.75	6.10
E_4 (psi)	600	3600	6600	9600	12,600	15,600	

* Equi-spaced $\text{Log}_{10} E_3$ Values Were Taken to Cover a Wide Range of E_3

Fig 19. Schematic of layered system for subbase analysis.

TABLE 7. k VALUES AT THE TOP OF 6-INCH SUBBASE
(ELASTIC LAYERED SOLUTIONS)

E_4 → / Log E_3 ↓	600	3,600	6,600	9,600	12,600	15,600
4.00	33	160	273	376	470	556
4.35	39	175	300	418	532	640
4.70	47	195	328	457	582	704
5.05	57	225	369	507	640	771
5.40	72	268	429	580	724	865
5.75	92	328	515	686	848	1003
6.10	118	410	635	836	1024	1202

(1) 0, 3, and 6 inches;

(2) 6, 9, and 12 inches; and

(3) 12, 15, and 18 inches.

Three models developed along with the transformations used for orthogonal polynomial analysis are given in Chapter 4 (Eqs 4.15 through 4.21).

Application of the theory of elasticity to the solutions of layered system requires certain essential assumptions regarding boundary and continuity conditions. These assumptions are therefore indirectly active on the models developed. Soils in each of the two layers are assumed to be homogeneous, isotropic, and linearly elastic materials. The subbase layer is assumed to be weightless, infinite in horizontal extent, and continuously in contact with the subgrade. The subgrade is assumed to be infinite in extent both horizontally and vertically downwards. Also, the subbase is assumed to be free of any normal and shearing stresses outside the loaded area.

The procedures to determine the values of subbase modulus E_3 and subgrade resilient modulus E_4 for input into the prediction models will be described in the rigid pavement design user's manual which is currently being prepared.

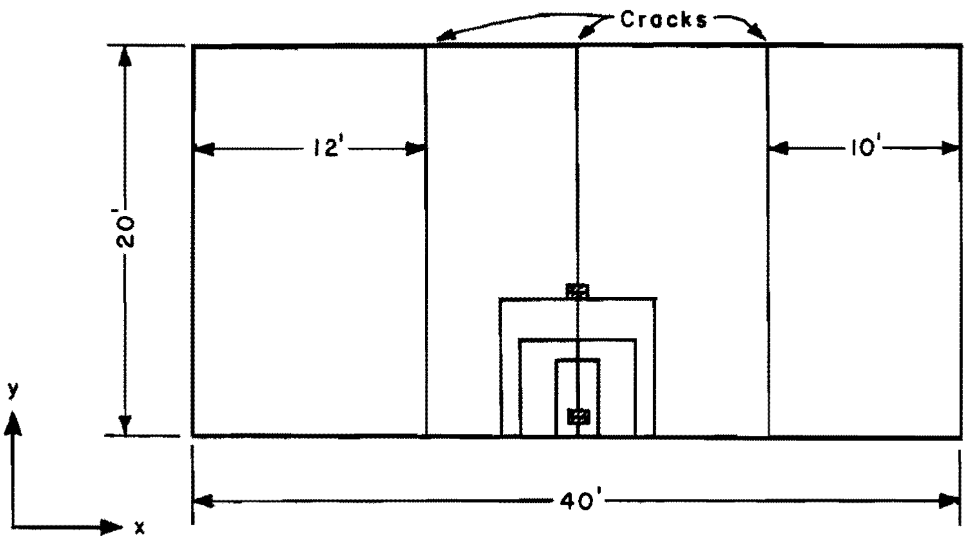
APPENDIX 6B. DEVELOPMENT OF MODEL FOR LOSS OF SUPPORT

A theoretical attempt is made to evaluate the effects of systems loss of support characterized by a term "erodability factor." This factor essentially defines the size of the area of pavement slab which experiences a complete loss of support due to erosion. Based upon experience and engineering judgment, three sizes and shapes of these areas, as explained in Fig 20, are chosen under a standard slab to define the erodability factors of one, two, and three. Resulting structures are analyzed for stresses and deflections by Program Slab 43 (Ref 30). The largest principal stresses are plotted against the modulus of support as shown in Fig 21.

It has been established at the AASHO Road Test that stresses produced in a concrete pavement slab are proportional to the number of load applications it can carry. Utilizing this observation, the equivalent modulus value can be determined, which would give the same largest principal stress in the slab as that given by the slab with partial support.

Table 8 gives the computed modified values of the modulus, k_M , for different erodability factors, E_f , and various initial modulus values, k_T . An orthogonal polynomial regression analysis is performed to predict the value of k_M to be used in RPS1. The equation with the transformations is presented in Chapter 4 (Eqs 4.22 and 4.23).

Theoretically E_f should be a function of factors such as precipitation, amount of water on and under the pavement, erosion, cross slope, grades, joint patterns and sealing efficiency, subbase materials, subgrade, compaction, slab thickness, and traffic loads and their repetitions, etc.



Stiffness in x-Direction Reduced by 75 % at the Cracks

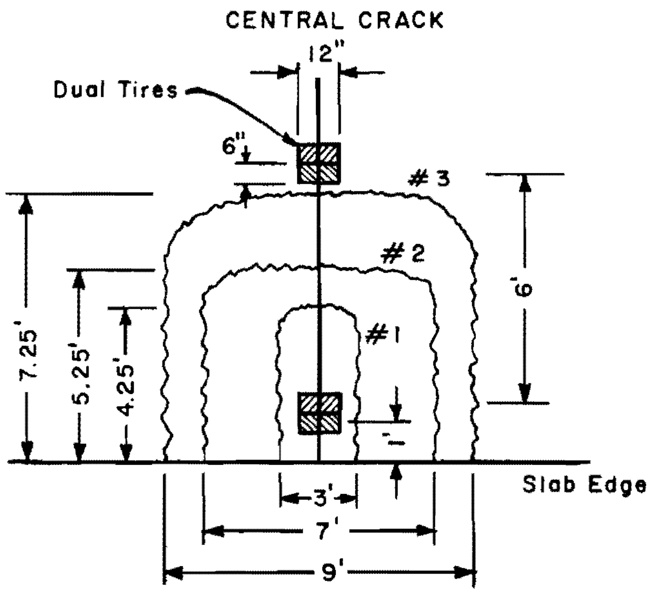
SLAB PROPERTIES

Thickness = 8"

Concrete Modulus = 5×10^6 psi

Poisson's Ratio = 0.25

4 Tires are 6000 lbs Each



Void Space	% Area of Slab	Erodability Factor
	0.00	0
# 1	1.59	1
# 2	4.59	2
# 3	8.16	3

Fig 20. Slab and support conditions for erodability analysis.

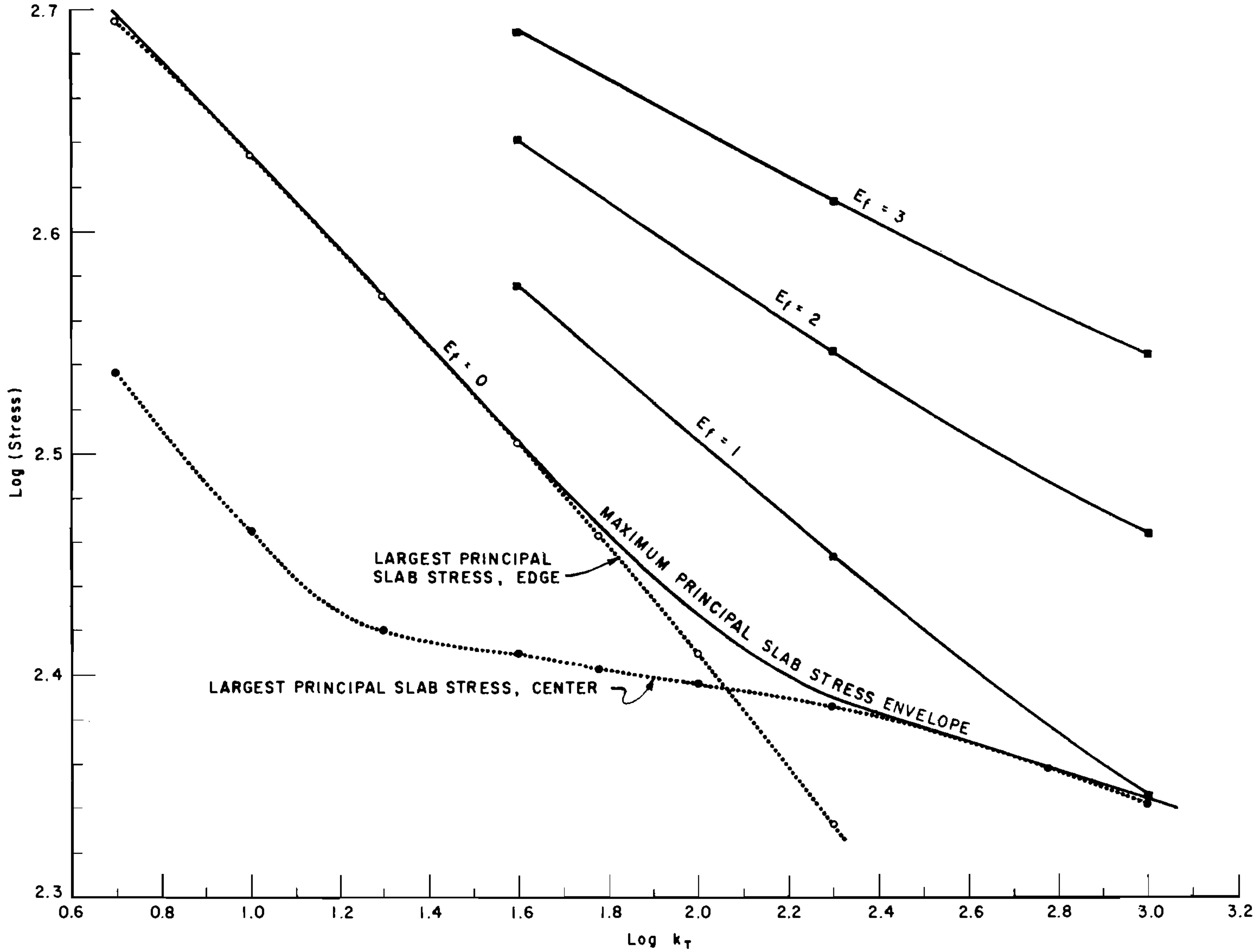


Fig 21. Largest principal stress curves for erodability analysis.

TABLE 8. DATA FOR ERODABILITY ANALYSIS AND PREDICTION EQUATION

	Log k_T	k_T	Log of Largest Principal Stress Produced, psi	Log k_M	Predicted Log k_M*
$E_f = 0.0$					
	1.6	39.8	2.506	1.600	1.600
	1.8	63.1	2.464	1.800	1.800
	2.0	100.0	2.428	2.000	2.000
	2.2	158.5	2.400	2.200	2.200
	2.4	251.2	2.383	2.400	2.400
	2.6	398.1	2.370	2.600	2.600
	2.8	630.9	2.357	2.800	2.800
	3.0	1000.0	2.344	3.000	3.000
$E_f = 1.0$					
	1.6	39.8	2.5750	1.280	1.273
	1.8	63.1	2.5410	1.435	1.451
	2.0	100.0	2.5060	1.600	1.600
	2.2	158.5	2.4710	1.765	1.751
	2.4	251.2	2.4380	1.939	1.933
	2.6	398.1	2.4050	2.160	2.176
	2.8	630.9	2.3750	2.515	2.511
	3.0	1000.0	2.3460	2.970	2.969
$E_f = 2.0$					
	1.6	39.8	2.6425	0.970	0.968
	1.8	63.1	2.6140	1.095	1.099
	2.0	100.0	2.5860	1.225	1.228
	2.2	158.5	2.5580	1.358	1.353
	2.4	251.2	2.5330	1.475	1.473
	2.6	398.1	2.5100	1.585	1.587
	2.8	630.9	2.4875	1.690	1.694
	3.0	1000.0	2.4650	1.795	1.793
$E_f = 3.0$					
	1.6	39.8	2.6910	0.730	0.730
	1.8	63.1	2.6690	0.835	0.834
	2.0	100.0	2.6475	0.935	0.938
	2.2	158.5	2.6250	1.045	1.041
	2.4	251.2	2.6040	1.140	1.142
	2.6	398.1	2.5830	1.240	1.239
	2.8	630.9	2.5640	1.330	1.332
	3.0	1000.0	2.5450	1.420	1.419

* The standard error for residuals in Log k_M = 0.0077 and R^2 value = 0.999.

APPENDIX 6C. DEVELOPMENT OF MODEL FOR ASPHALT CONCRETE OVERLAY DESIGN

A model for the analysis of composite structures resulting from asphalt concrete overlays provided over cement concrete pavements is developed by using layered elastic theory. Considering the correlations developed between stress and performance using the Road Test data (Ref 58), it can reasonably be assumed that a pavement overlay combination is equivalent in performance to "an equivalent concrete thickness" if both experience the same maximum tensile stresses. It is assumed further that such an equivalent concrete thickness can be analyzed by the performance model used to analyze rigid pavements.

Figure 22 describes two such equivalent structures. The following procedure is adopted for development of the model for the equivalent concrete thickness, based on the above assumption and using layered elastic theory.

As regards the large number of variables affecting the stress in the layered system formulated for analysis, the structure below the concrete slab is represented by the single parameter, the modulus of support k . Three-layered structures, fairly representative of usual field designs, were chosen with the layered analysis for their deflections giving respective k values of 40, 200, and 1000 psi. A load of 9000 pounds with 60 psi pressure was chosen for analysis. The structures are shown in Fig 23.

Keeping in view the polynomial regression analysis to be attempted to formulate a prediction model, a complete factorial analysis of the involved variables was desired. The following four most important variables were chosen for analysis:

(1) concrete slab thickness: 6, 8, 10, and 12 inches;

(2) asphalt concrete overlay thickness: 3, 6, 9, 12, and 15 inches;

(3) modulus of asphalt concrete: 100,000, 450,000, and 800,000 psi; and

(4) modulus of support values: 40, 200, and 1000 psi.

For achieving an orthogonal polynomial fit for data, the variables were equally spaced. Log k was used in place of k . Poisson's ratio for

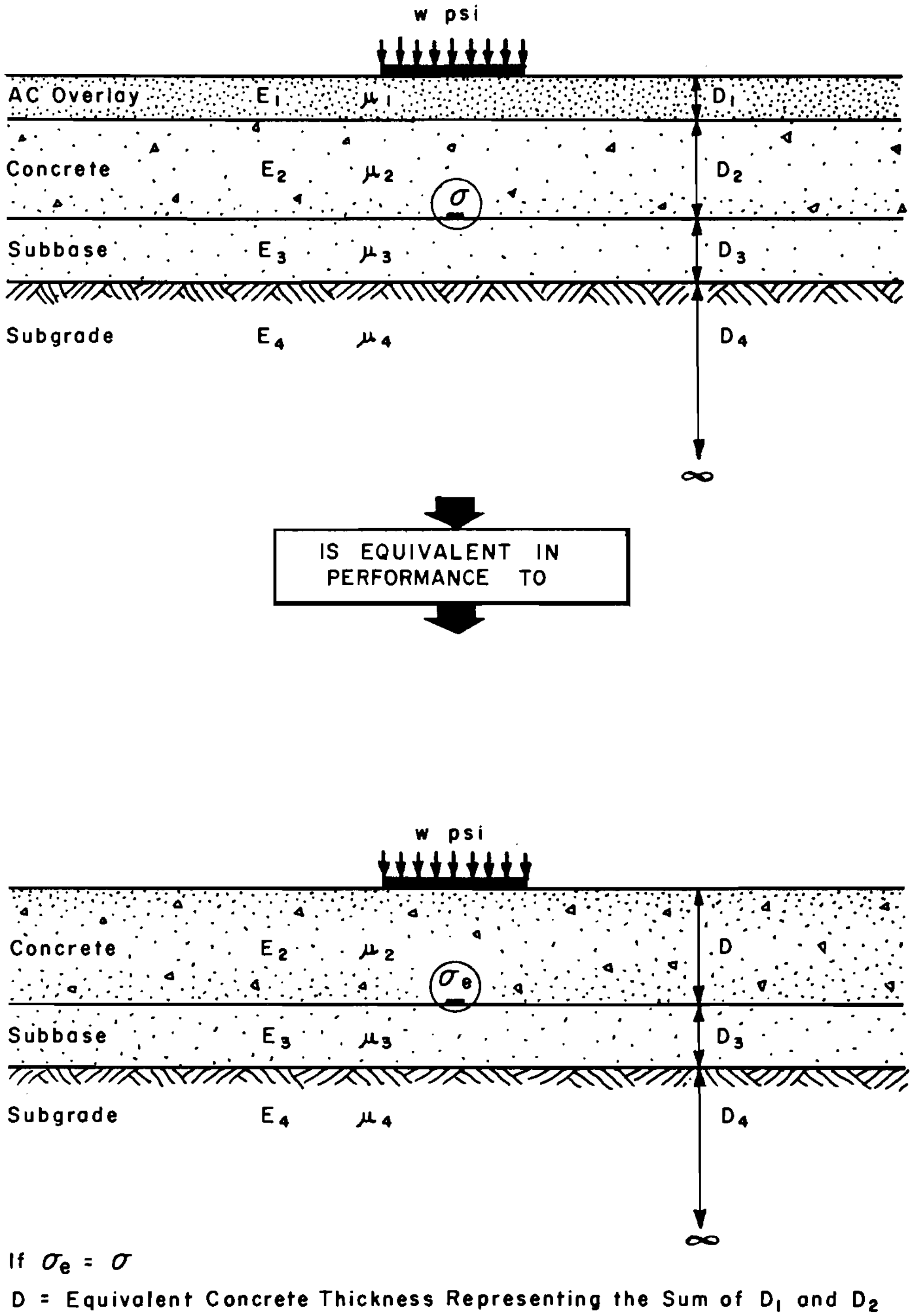
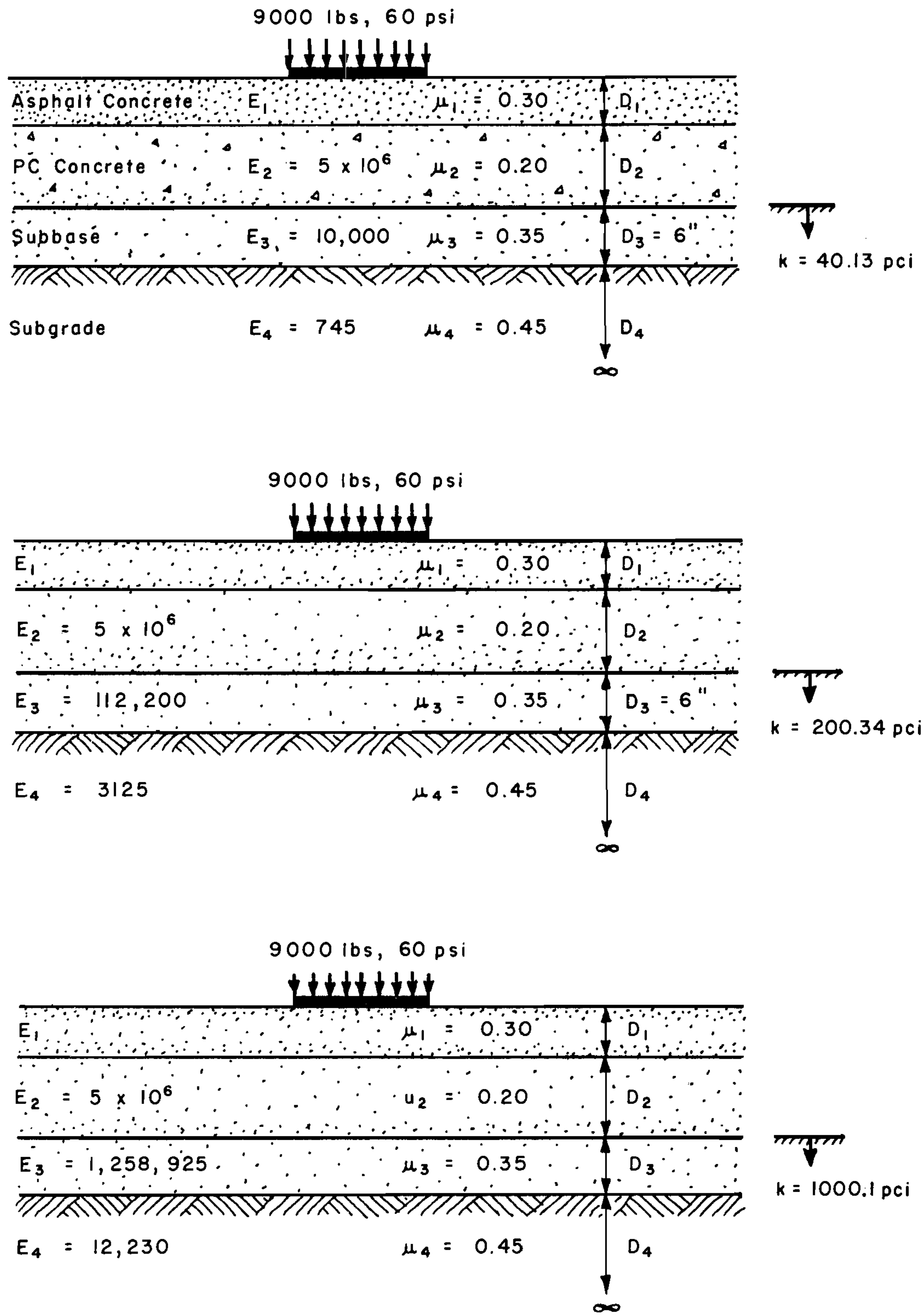


Fig 22. Equivalent layered system for concrete pavement overlayed with asphalt concrete.



Variations for Analysis

E_1 = 10^5, 4.5×10^5, 8.0×10^5 psi $\quad$ D_2 = 6, 8, 10, 12 in.

D_1 = 3, 6, 9, 12, 15 in. $\quad$ k = 40, 200, 1000 pci

Fig 23. Layered structures analyzed for the development of model for AC overlay design.

concrete and overlays, as well as the modulus value for concrete, was held constant for the analysis.

Each structure with a particular concrete thickness, AC modulus, and k value was analyzed for each overlay thickness by the LAYER Program. A number of problems with varying concrete thicknesses and no overlay were also solved. Curves of the type shown in Fig 24 were plotted for overlay thickness versus maximum stress at the bottom of concrete and concrete thickness versus the maximum stress.

The equivalent thickness of concrete corresponding to each overlay thickness was picked from these graphs. Figures 25 and 26 show comparative plots of overlay thicknesses versus equivalent concrete thicknesses for different k values, asphalt concrete moduli, and concrete thicknesses. About 250 problems were solved by the LAYER Program to develop this data.

An orthogonal polynomial regression analysis was carried out for 180 data points. The overlay thickness of 15 inches, considered to be relatively large, was dropped from the analysis to achieve a better fit of data. A complete study of main effects and interactions was carried out to explore all possible combinations of variables which could help to improve the predictions. The developed model for equivalent concrete thickness is given in Chapter 4 (Eqs 4.28 and 4.29).

The following limitations can be stated with regard to the model developed:

(1) Composite structures are analyzed by the elastic layered theory and, therefore, all the assumptions relating to the theory are active on the model developed.

(2) A number of material properties and the load applied for the layered analysis were held constant for the model.

(3) The deterioration of the existing PCC pavement at the time of the first overlay or that of composite pavement at the time of subsequent overlay is not considered in this model.

(4) Analysis is based on equivalent stress concept. The assumption is well supported by the observations at the AASHO Road Test but the following, as stated by Hudson and Scrivner (Ref 58), should be held as regards this assumption:

> Theory says that stresses in concrete slabs are influenced by many variables, including load, thickness, support, modulus of elasticity, Poisson's ratio and the contact area of the applied load. Excluding load and thickness, the other factors listed were held constant for the

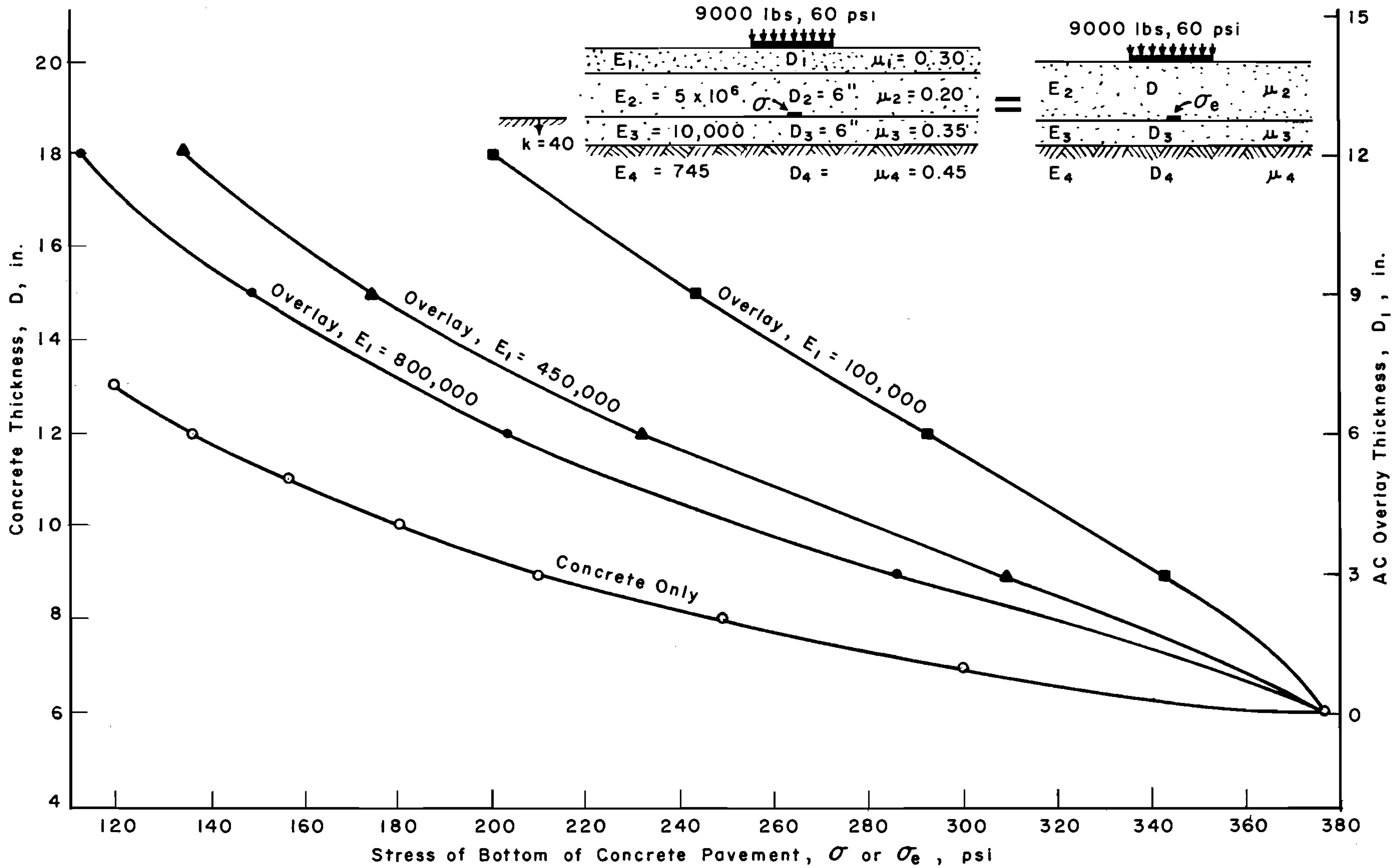


Fig 24. Plots of stresses at the bottom of concrete.

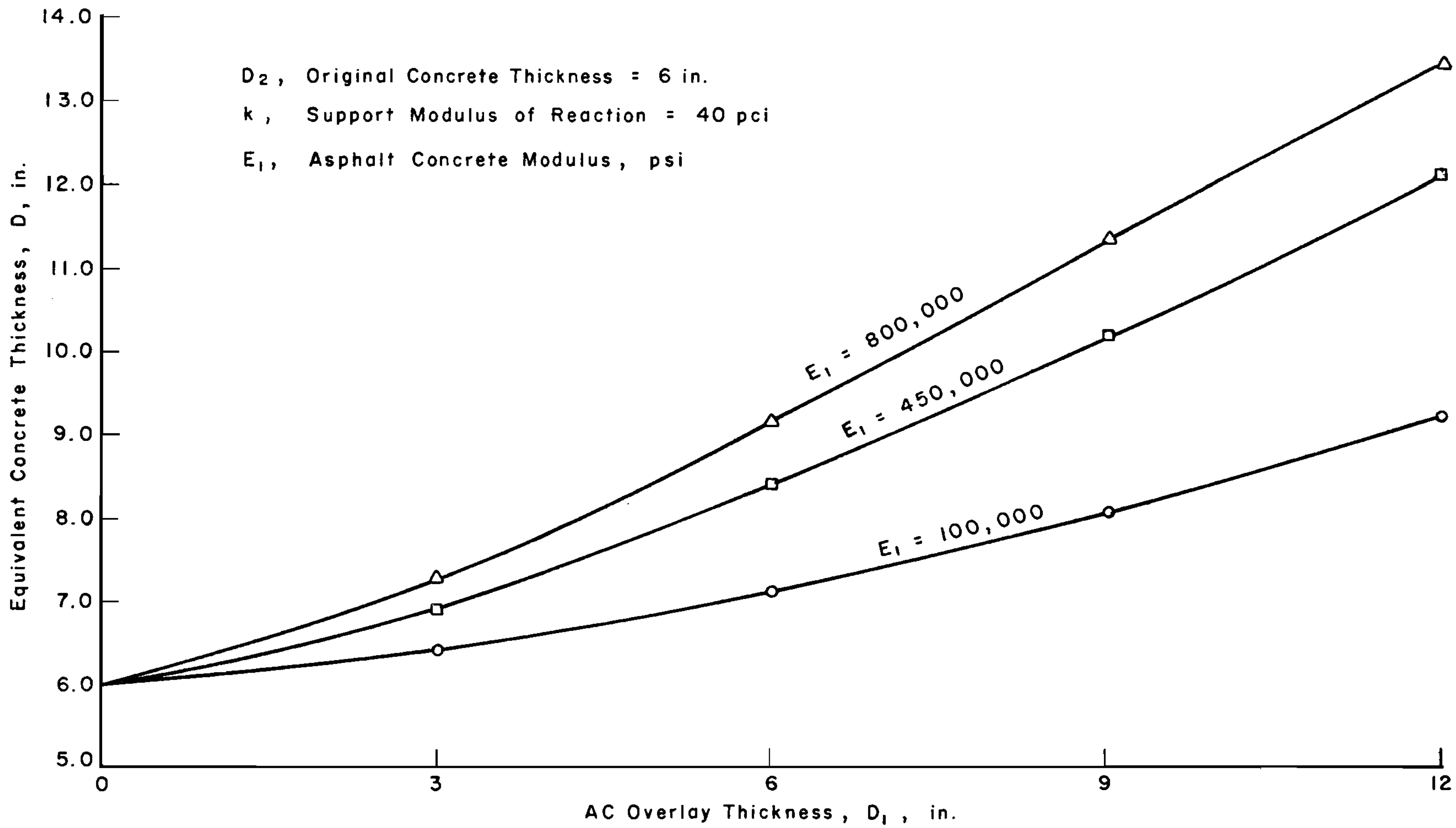


Fig 25. Equivalent concrete thicknesses for different overlay thicknesses over 6-inch PCC pavement.

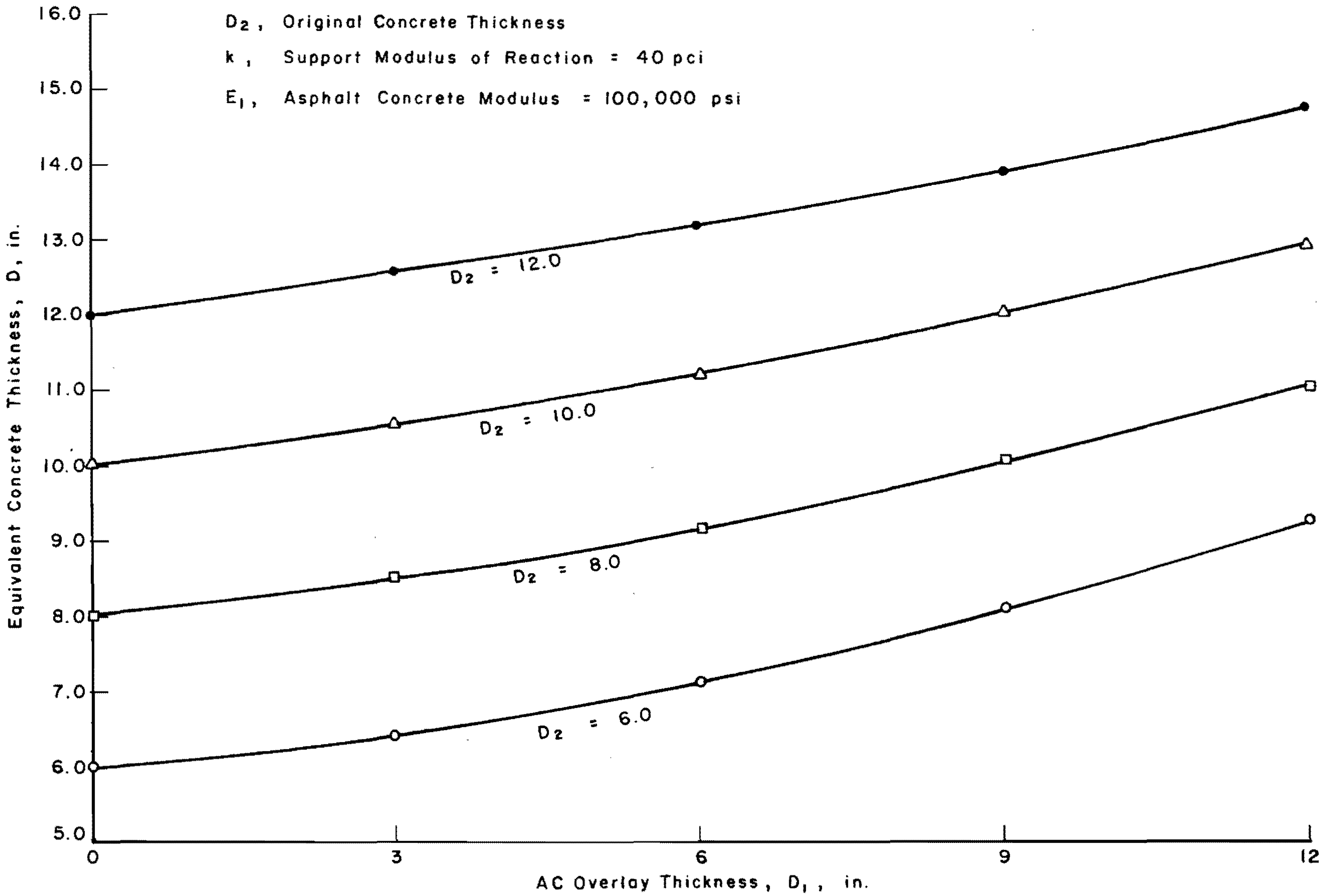


Fig 26. Equivalent concrete thicknesses for different overlay thicknesses over 6, 8, 10, and 12-inch PCC pavements.

Road Test pavements, within the limits of measurement error. With these other factors held constant the stresses obtained from strain measurements for the study pavement proved to be reasonably good predictors of the performance which these pavements ultimately gave.

It is not known whether these same relationships between stress and performance could hold if the variations in stress were due to factors other than load or slab thickness, presumably they would. However, the factors and interactions involved in such a determination are so complicated as to require additional experimental evidence...

APPENDIX 7

MODELS FOR CALCULATING TRAFFIC DELAY COST DURING AN OVERLAY CONSTRUCTION

APPENDIX 7. MODELS FOR CALCULATING TRAFFIC DELAY COST DURING AN OVERLAY CONSTRUCTION

The stops and speed reductions of traffic during an overlay construction are assumed to follow certain speed profiles, as shown in Fig 27. Five different methods of handling traffic during an overlay construction are built into the program and any one can be specified by the designer. The methods are described in Fig 28.

The procedure for computing traffic delay cost is as follows:

Average daily traffic ADT_t at the time t_n when the n^{th} overlay is provided is

$$ADT_t = ADT_i \ (1 + G_F . t_n) \tag{7A.1}$$

where ADT_i = initial one direction average daily traffic and G_F = average daily traffic growth factor per year.

If P_{ph} is the percent of ADT_t arriving each hour of overlay construction, vehicles arriving per hour, V_{ph} , are

$$V_{ph} = ADT_t \cdot \frac{P_{ph}}{100} \tag{7A.2}$$

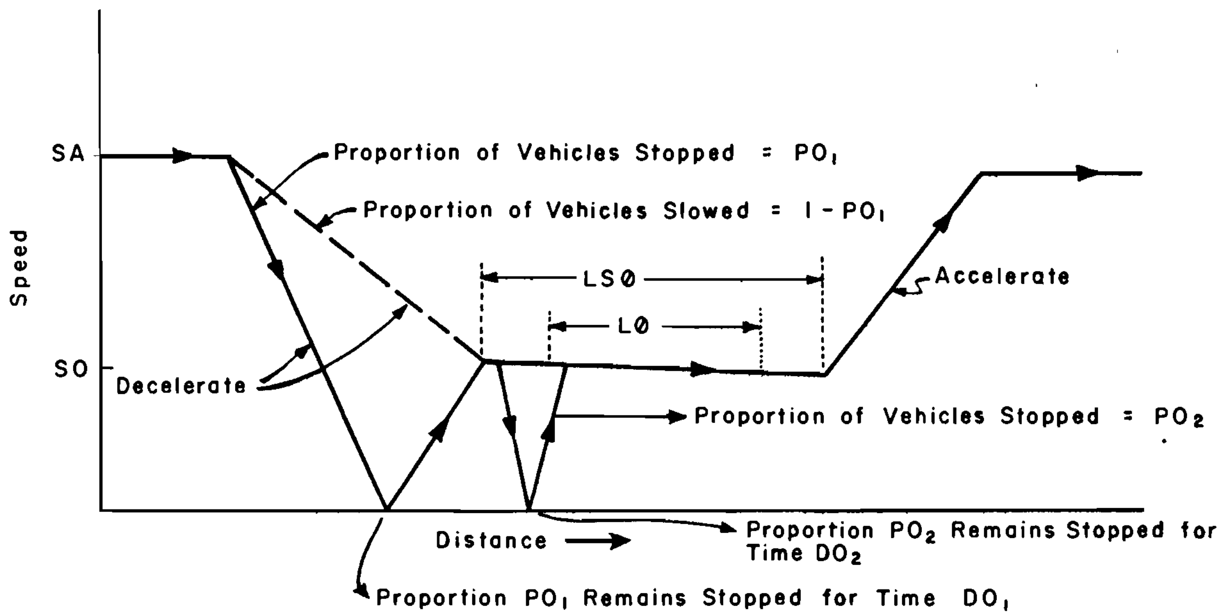
Traffic delay cost in overlay direction is calculated in three parts.

(1) The proportion of vehicles, PO_1 , stopped by congestion gives rise to the following cost:

$$CO_c = CO_1 + CO_2 + CO_3 \tag{7A.3}$$

where

CO_c = cost of congestion per vehicle;



SA = Approach Speed

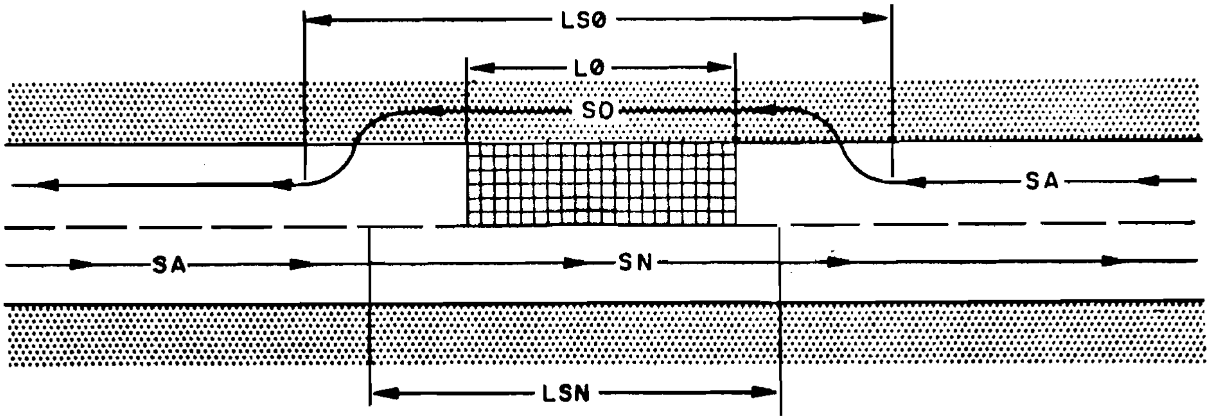
SO = Speed Through Restricted Zone
* (SN) in Overlay Direction

LSØ = Length of Restricted Area
* (LSN) in Overlay Direction

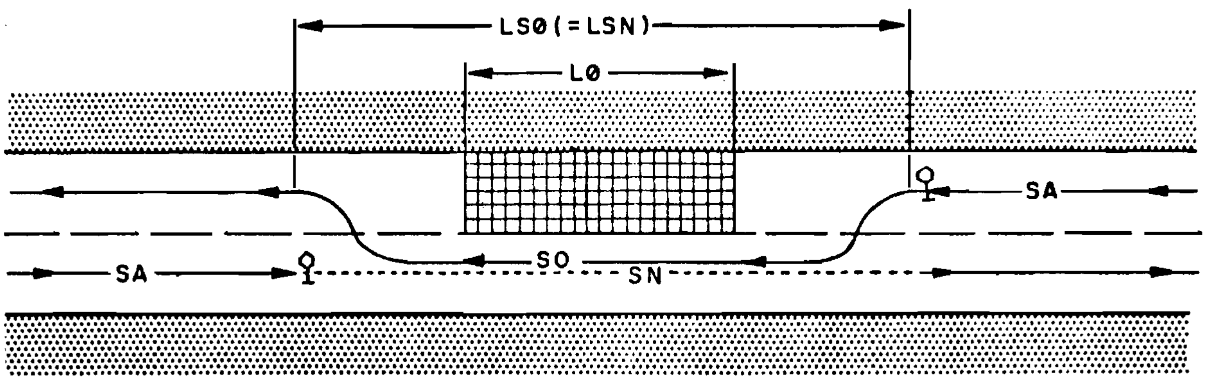
LØ = Length of Area Being Overlayed

* In Parentheses are the Corresponding Values in Nonoverlay Direction. There are Similar Corresponding Values for PN_1, PN_2, DN_1, DN_2

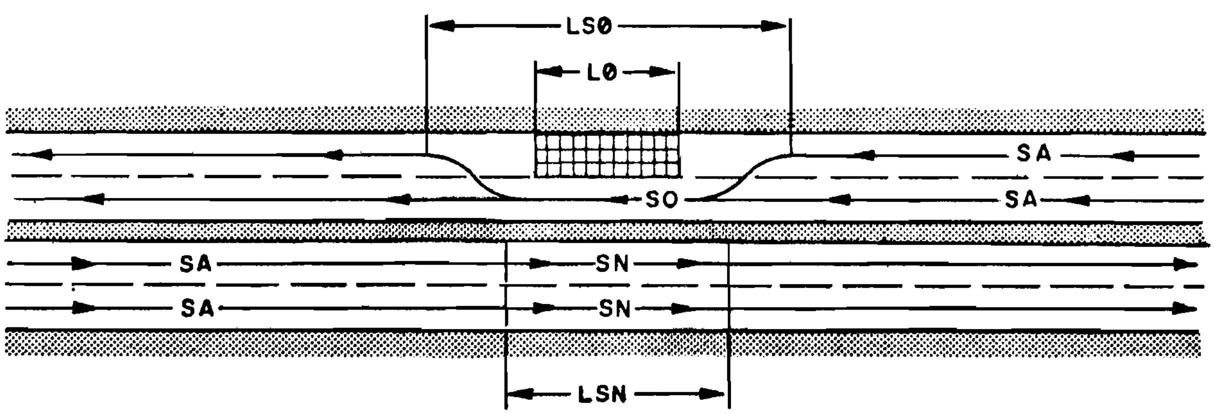
Fig 7A.1. Speed profiles for vehicles during overlay operation.



(a) Model I: traffic routed to shoulder.



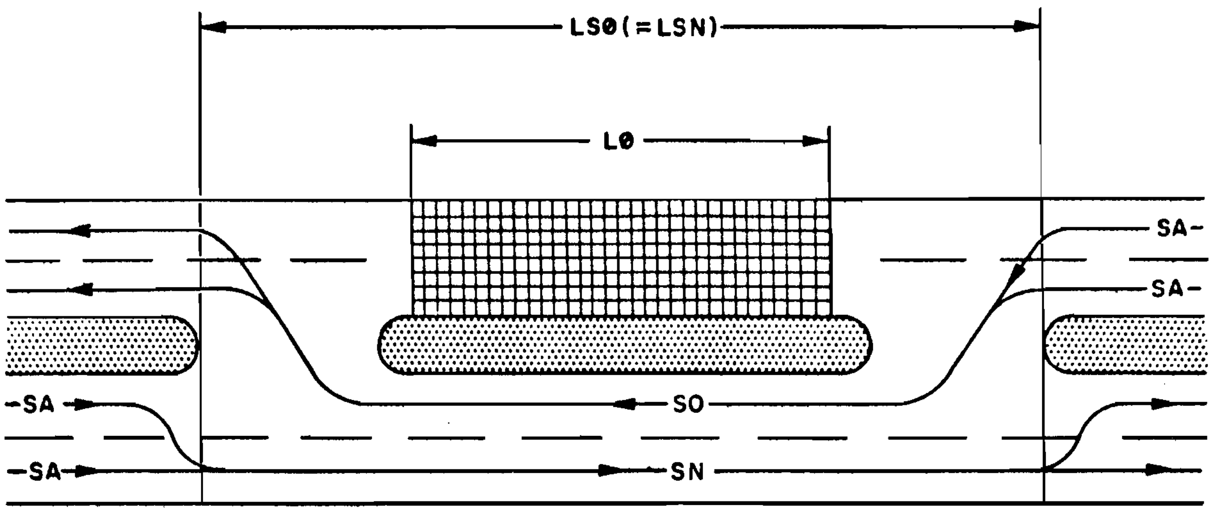
(b) Model II: alternating traffic in one lane.



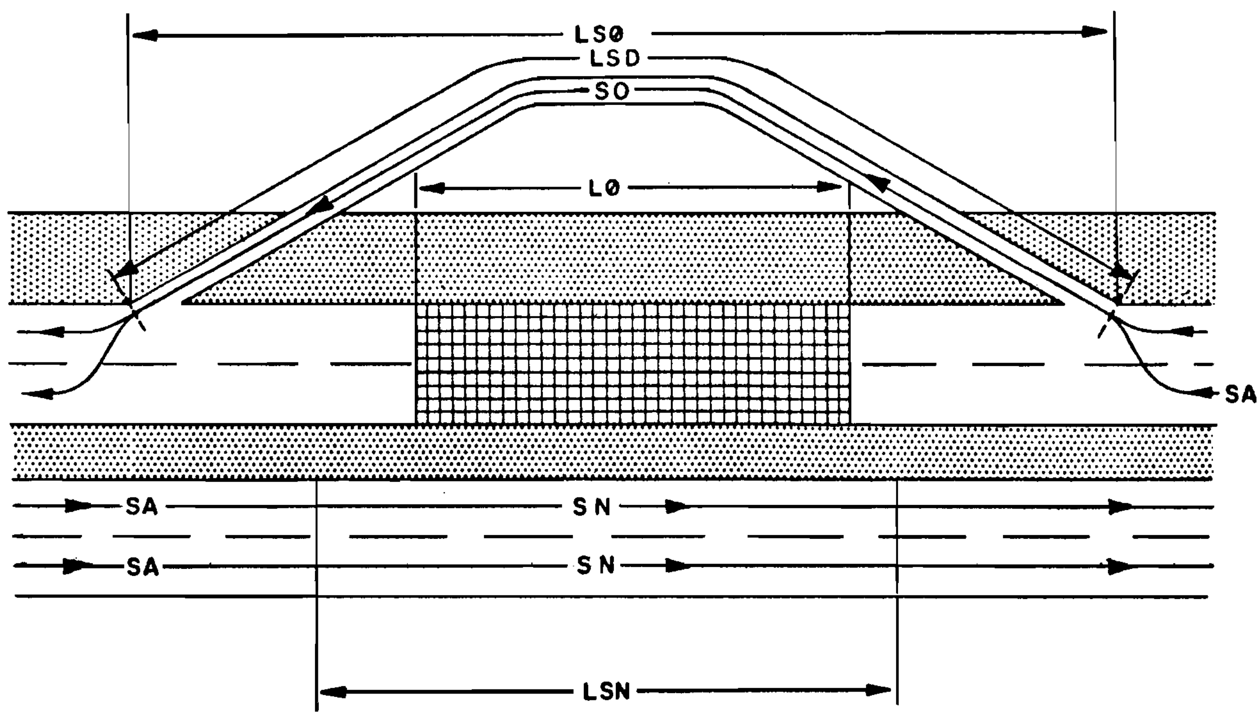
(c) Model III: two lanes merge, nonoverlay direction not affected.

Fig 28. Models for handling traffic during overlay construction (after Scrivner et al, Ref 104).

(Continued)



(d) Model IV: overlay direction traffic routed to nonoverlay lanes.



(e) Model V: overlay direction traffic routed to frontage road or other parallel route.

Fig 28. (Continued from previous page.)

CO_1 = cost of one cycle of stopping from and returning to the approach speed per vehicle;

CO_2 = cost of idling and time loss per vehicle;

CO_3 = cost of driving at the reduced speed through the restricted area per vehicle

(2) The rest of the vehicles, $1 - PO_1$, which are not stopped but travel at the reduced speed incur the following cost:

$$CO_s = CO_3 + CO_4 \tag{7A.4}$$

where

CO_s = cost of slowing per vehicle;

CO_3 = cost of driving at reduced speed per vehicle;

CO_4 = cost of one cycle of slowing to the through speed and returning to the approach speed per vehicle.

Cost of disturbances in the regular flow of traffic per hour is therefore

$$CO_D = V_{ph} \cdot PO_1 \cdot CO_c + V_{ph} \cdot (1 - PO_1) \cdot CO_s \tag{7A.5}$$

(3) A proportion, PO_2, of all vehicles passing through the restricted area is stopped due to movement of overlay equipment and personnel. The cost, CO_p, is the sum of two following costs:

$$CO_p = CO_5 + CO_6 \tag{7A.6}$$

where

CO_5 = cost of one cycle of stopping from and returning to the reduced speed in the restricted area per vehicle;

CO_6 = cost of idling while stopped per vehicle.

Cost per hour due to being stopped by equipment and personnel, CO_E , is, therefore,

$$CO_E = V_{ph} \cdot PO_2 \cdot CO_p \tag{7A.7}$$

Total traffic delay cost per hour in the overlay direction is thus

$$CO_{DE} = CO_D + CO_E \tag{7A.8}$$

The above analysis can be reached for the nonoverlay direction by replacing O in each term by N . The total traffic delay cost per hour in the nonoverlay direction, CN_{DE} , is therefore

$$CN_{DE} = CN_D + CN_E \tag{7A.9}$$

Assuming equal traffic per hour in the nonoverlay direction, total traffic delay cost per hour in both directions, C_T , is thus

$$C_T = CO_{DE} + CN_{DE} \tag{7A.10}$$

If the production rate of overlaying material is denoted by P_r cubic feet per hour, the number of hours to construct one square yard of overlay, H_{sy} will be

$$H_{sy} = \frac{T_n}{36} \cdot \frac{1}{P_r} \tag{7A.11}$$

where T_n is the thickness of the n^{th} overlay, inches.

Total cost of traffic delay during the n^{th} overlay, C_n , per square yard of pavement will be

$$C_n = H_{sy} \cdot C_T \tag{7A.12}$$

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