OPTIMAL DESIGN OF FLEXIBLE PAVEMENT
SECTIONS

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BY

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JHRP

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OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

To: J. F. McLaughlin, Director
Joint Highway Research Project

From: H. L. Michael, Associate Director
Joint Highway Research Project

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Project No: C-36-52H

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The attached technical paper entitled "Optimal Design of Flexible Pavement Sections" has been prepared by Messrs. S. S. Hejal, S. R. Yoder, and J. C. Oppenlander. The paper has been submitted to the Highway Research Board for presentation at the 1970 Annual Meeting and for subsequent publication. The purpose of this systems analysis was to develop a rational method for the optimal selection of flexible components. Minimum-cost thicknesses are determined for flexible pavements to satisfy the demands of traffic and environment on the system of pavement structure and soil support. Each flexible pavement section fulfills the design objectives for the least total cost.

The paper is presented to the Board for approval of presentation and publication by the Highway Research Board.

Respectfully submitted,

Harold L. Michael
Harold L. Michael
Associate Director

HLM/rg

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Technical Paper

OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

by

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Joint Highway Research Project

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Purdue University

Lafayette, Indiana

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OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

INFORMATIVE ABSTRACT

Although several methods are available for the design of flexible pavements, no existing technique explicitly considers the optimal combination of flexible pavement components to minimize the total in-place cost of the pavement system. The purpose of this systems analysis was to develop a rational method for the optimal selection of the arrangement of the various pavement components. This cost minimization must be realized within the boundary conditions that are imposed by the practical limitations of the design parameters.

The design model consists of an objective function and various constraint equations. The total cost of the pavement system is quantitatively described by this objective function, and a minimum-cost solution is obtained for each combination of material costs and design conditions. The various constraining equations quantify the boundary conditions to which the design of a flexible pavement is subject. These physical limitations complete the realism of the mathematical model in describing the real-world situation of flexible pavement design. The design model was solved by a modified linear programming technique.

In developing practical solutions to the design model, optimal flexible pavements are designed for cross-sections without subbase, cross-sections with subbase through shoulders, and cross-sections with subbase and subdrains. The design requirements for the various components are predicated on the design parameters of traffic conditions, soil support values, pavement material characteristics, environmental effects, and

pavement performance requirements and on unit costs of pavement components. Substantial cost savings result in the selection of flexible pavement sections by this design procedure.

OPTIMAL DESIGN OF FLEXIBLE PAVEMENT SECTIONS

INTRODUCTION

The primary objective of highway pavement design is to provide an acceptable roadway surface that can withstand the deteriorating effects of traffic and environment for the service life of the facility. In addition, the pavement structure must adequately serve the demands of the road users at an acceptable level of performance. A properly designed, constructed, and maintained pavement is a major factor in providing economical, efficient, safe, convenient, and comfortable highway travel. This goal is an integral part of the total highway transportation program.

Although several design techniques are available for determining reasonable thicknesses of flexible pavements to satisfy the specified design parameters, no present method explicitly considers an optimization of flexible pavement components to minimize the total cost of the pavement system. Of course, this cost minimization must be realized within the boundary constraints imposed by the selected values of the design parameters. The purpose of this systems analysis was to develop a rational method for the optimal design of flexible pavement sections.

The objective of flexible pavement design in this investigation is to select the various pavement components so that the total pavement cost is minimized within the limitations of the various design parameters. Minimum-cost designs are determined for flexible pavements to satisfy the demands of traffic and environment on the system of pavement structure and soil support. Therefore, this technique affords a

practical and economical solution to the problem of designing flexible pavements. This approach to design embodies the essence of sound engineering.

CONCEPTUAL MODEL

A flexible pavement distributes the traffic loads through a system of pavement components to the subgrade. These pavement layers are generally identified as surface, base, and subbase. Several different thickness combinations of the materials comprising the various components may adequately satisfy the structural design of the highway pavement. However, all satisfactory thickness arrangements may not provide an economical solution to the engineering problem of pavement design. In general, only one pavement structure is an optimal selection of the flexible pavement components for the designated design conditions.

The concept for this flexible pavement design procedure is illustrated by the logic diagram in Figure 1. The total pavement system is described by the various design parameters which represent traffic conditions, soil support values, pavement material characteristics, environmental effects, and pavement performance requirements. In addition, unit costs of pavement components and alternate cross-section designs are considered in the selection of the optimum flexible pavement section.

The structural requirements of flexible pavements are predicated on an estimated number of equivalent 18-kip single-axle load repetitions and on an appropriate measure of the soil support afforded by the subgrade. The elements of pavement performance and environment are also incorporated as initial and terminal serviceabilities and regional factor, respectively. The combined effect of traffic loading, soil support, pavement performance, and environment is denoted as a structural number (SN) according to the interim design guide of the American

Figure 1

Association of State Highway Officials for flexible pavements. (1)*

Pavement component thicknesses are then selected to reproduce the specified structural number by a linear combination of layer thickness times its coefficient of relative strength. A minimum pavement thickness is equal to the summation of the component thicknesses.

Consideration of significant environmental factors, such as depth of frost penetration, provides another control on the selection of a minimum pavement thickness. This design procedure specifies a minimum pavement thickness ($T_{\min}$) to account for various influencing environmental conditions. This minimum thickness is based on a design procedure which requires a selected design wheel load and a specified soil support value. The greater minimum thickness value becomes the design requirement.

To account for varying design practices, several types of pavement cross-sections are available as possible alternatives in this procedure for designing flexible pavements. These arrangements include cross-sections without subbase, cross-sections with subbase through shoulders, and cross-sections with subbase and subdrains. Finally, the unit costs of the pavement components are specified to permit the design of an acceptable pavement structure for the least cost. This cost-effectiveness approach provides both an optimal and a practical solution to the problem of flexible pavement design.

*Numbers in parentheses refer to articles listed in the Bibliography.

In a real sense, the minimum thicknesses represent design constraints and not design objectives. The design objective is to produce a flexible pavement system at the least total cost within the specified boundary conditions. The in-place unit costs of the component materials depend on the locale in which the flexible pavement is to be constructed. In addition to the traffic loading, soil support, pavement performance, and environment constraints, practical limitations on layer thicknesses are specified in concurrence with present highway construction practices.

DESIGN MODEL

The logic diagram for this optimal design of flexible pavements is structured in Figure 1. A detailed description of this design technique is presented under the following categories of Design Parameters, Design Sections, and Optimization Model. These sections provide the various computational procedures and design features for determining the optimal selection of flexible pavement sections.

Design Parameters

The design parameters represent the various measures of traffic conditions, soil support, pavement material properties, environmental effects, and pavement performance requirements. The results of these evaluations provide the summary quantities that are necessary for the optimal design of flexible pavements.

The initial measure of the stability of the subgrade soil is determined by the standard California bearing ratio test. This soil strength is then translated into the soil support value (SSV) as defined by the American Association of State Highway Officials. (1) In this study the following equation was developed to relate soil support values to California bearing ratio measures:

$$SSV = 4.90 \log_{10} (CBR)$$

where SSV = soil support value and

CBR = California bearing ratio.

The traffic conditions are expressed as the number of 18-kip single-axle load repetitions for the service life of the pavement. These load applications are estimated from an evaluation of the following formula:

$$W = 365 (TF) (DP)$$

where W = total number of equivalent 18-kip single-axle load repetitions during the pavement design period,

TF = truck factor (18-kip single-axle load applications per day), and

DP = design period (years).

To develop a measure of the truck factor, a correlation was derived between the number of 18-kip single-axle load applications and the percentages of various truck types in the traffic streams. The following expression was obtained from loadometer data collected on highways in Indiana:

$$TF = \left[\frac{(ADT_1) + (ADT_2)}{4} \right] \left[\frac{11.7(TR)(LU) + 0.83(TR)(LU)(CT)}{10,000} \right]$$

where TF = truck factor (18-kip single-axle load applications per day),

ADT_1 = average daily traffic volume at the start of the design period (vehicles per day in both directions),

ADT_2 = average daily traffic volume at the end of the design period (vehicles per day in both directions),

TR = percentage of all trucks,
 CT = percentage of combination trucks, and
 LU = truck lane usage factor (1.0, 0.9, and
 0.8 for two-, four-, and six-lane
 highways, respectively).

The various measures of traffic conditions, soil support, environmental effects, and pavement performance requirements are now combined into a single design parameter defined as the structural number (SN). Two nomographs have been prepared by the American Association of State Highway Officials to quantify this structural requirement. (1) However, the following equation was developed from these nomographs to use in the computer program for this design procedure:

$$\begin{aligned} \log_{10}(W) = & 9.36 \log_{10} [(SN) + 1] - 0.20 \\ & + \log_{10} \left[\frac{(CO) - (P)}{(CO) - 1.5} \right] \bigg/ \left[0.40 + \frac{1094}{[(SN) + 1]^{5.19}} \right] \\ & + 0.37756 [(SSV) - 3.0] - 0.97 \log_{10} (RF) \end{aligned}$$

where W = total number of equivalent 18-kip single-axle
 load repetitions during the pavement design period,
 SN = structural number,
 CO = initial pavement serviceability index (4.2 for
 all highways),
 P = terminal pavement serviceability index,
 SSV = soil support value, and
 RF = regional factor. (2)

The effects of the environment are numerically summarized in the regional factor, and the desired pavement performance is specified by selected values for the initial and terminal pavement serviceability indices. An iterative procedure is used to solve the above equation for the structural number of a particular design situation.

Another consideration of environmental influences is to determine a minimum thickness as a design against the detrimental effects of frost action and the loss of subgrade strength in the spring break-up period. Design charts that were developed by L. D. Hicks provide correlations between bearing capacity and California bearing ratio and between pavement thickness and bearing capacity. (3) Adverse subgrade conditions are represented by using a two-day soaked value for the selected California bearing ratio. The following relationships were prepared from these design charts for 9-kip and 10-kip wheel loads, respectively:

$$T_{\min.(9)} = 4.723 + \frac{61.037}{(\text{CBR})^{1.05}} - 45.18 e^{-(\text{CBR})}$$

$$T_{\min.(10)} = 4.423 + \frac{52.706}{(\text{CBR})^{0.90}} - 19.884 e^{-(\text{CBR})}$$

where $T_{\min.(9)}$ = minimum pavement thickness for 9-kip design wheel load (inches),

$T_{\min.(10)}$ = minimum pavement thickness for 10-kip design wheel load (inches), and

CBR = California bearing ratio for reduced strength conditions.

The 10-kip wheel load is considered satisfactory for the design of primary highways, while the 9-kip wheel load is applicable for flexible pavements on secondary routes. In the computer input for this design

model, the highway engineer specifies the design wheel load for either a primary or a secondary highway. This minimum-thickness determination accounts for environmental effects by highway classification and provides another realistic constraint in selecting optimal flexible pavement sections.

The characteristics of each pavement material are described by the in-place density and the coefficient of relative strength. These values depend on the local materials that are used in the construction of flexible pavements. The evaluation of the pavement material characteristics permits the application of the design model for the prevailing construction practices.

The above descriptions numerically define the various design components of the flexible pavement system. Although the selected equations provide reasonable evaluations of these parameters, other expressions can be used to satisfy local design conditions.

Design Sections

Because reasonable variations exist in the design of highway elements, three acceptable cross-sections were selected for two-lane and divided multi-lane highways to provide several alternative designs in the model. These arrangements include the following distinct designs:

1. Cross-sections without subbase (S_1),
2. Cross-sections with subbase (S_2)
 - a. Extended through the shoulders for two-lane highways and
 - b. Extended through the right shoulder with subdrain under the left shoulder for divided multi-lane highways, and

3. Cross-sections with subbase and subdrains under both shoulders (S_3)

Typical details of these cross-sectional designs are illustrated in Figures 2, 3, 4, and 5, respectively. The shoulder designs are further detailed in Figure 6 for cross-sections with subbases and with subdrains.

Of course, additional cross-sectional arrangements may be incorporated into this design model. Because each section represents a different design, an objective function is required for each cross-section to permit the optimal selection of flexible pavement sections. The best design is then that cross-section which minimizes the total pavement cost for the specified design parameters.

Optimization Model

The optimal design of flexible pavement sections is depicted by the following objective functions for the three different design sections:

1. Cross-sections without subbase;

$$\begin{aligned} \text{Min. } S_1 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} \right] d_1 + \left[\frac{C_2 D_2 L k_j}{12 \times 2000} \right] d_2 \\ & + \left[\frac{C_3 D_3 L k_j}{12 \times 2000} \right] d_3 + E_L + H_L \end{aligned}$$

Figure 2 Typical Cross-Section Of A Flexible Pavement Without Subbase
For A Four-Lane Highway, One Direction.

Figure 3 Typical Cross-Section Of A Flexible Pavement With Subbase Through The Shoulder For A Two-Lane Highway.

Figure 4 Typical Cross-Section Of A Flexible Pavement With Subbase Through The Shoulder For A Four-Lane Highway, One Direction.

Figure 5 . Typical Cross Section Of A Flexible Pavement With Subbase Drain
For A Two-Lane Highway.

Figure 6 Shoulder Details.

2. Cross-sections with subbase through shoulders;

$$\begin{aligned}
 \text{Min. } S_2 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_1 \\
 & + \left[\frac{C_2 D_2 L k_1}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_2 \\
 & + \left[\frac{C_3 D_3 L k_1}{12 \times 2000} + \frac{C_4 A}{12 \times 27} \right] d_3 \\
 & + \left[\frac{C_4 (L+A)}{12 \times 27} \right] d_4 + E_f + H_f + M_f - Y_f
 \end{aligned}$$

3. Cross-sections with subbase and subdrains;

$$\begin{aligned}
 \text{Min. } S_3 = & \left[\frac{C_1 D_1 L k_1}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_1 \\
 & + \left[\frac{C_2 D_2 L k_1}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_2 \\
 & + \left[\frac{C_3 D_3 L k_1}{12 \times 2000} + \frac{C_4 B}{12 \times 27} \right] d_3 \\
 & + \left[\frac{C_4 (L+B)}{12 \times 27} \right] d_4 + E_f + H_f + N - Z_f
 \end{aligned}$$

where S = total cost of pavement system (dollars per longitudinal foot),

C_i = unit cost of material 'i' (dollars per ton for materials 1, 2, 3, 5, and 8, dollars per cubic yard for materials 4 and 6, and dollars per foot for material 7),

D_1 = density of material '1' (pounds per cubic foot),

L = pavement width (24 ft for two-lane and one-way section of divided four-lane highways and 36 ft for one-way section of divided six-lane highways),

d_1 = thickness of material '1' (inches),

i = 1 for bituminous surface, 2 for stabilized base, 3 for compacted aggregate base, 4 for granular subbase, 5 for bituminous shoulder surface, 6 for subdrain granular fill, 7 for subdrain pipe, and 8 for wearing surface,

k_j = adjustment factor for increase in width of pavement layers;

k_1 = 1.00 for first layer,

k_2 = 1.04 for second layer,

k_3 = 1.08 for third layer, and

k_4 = 1.12 for fourth layer,

E_s = cost of shoulder (dollars per longitudinal foot),

For two-lane highways;

$$E_1 = 20 \times 3.0 \left[\frac{C_5 D_5}{12 \times 2000} \right] \\ + 31 \times 6.0 \left[\frac{C_3 D_3}{12 \times 2000} \right]$$

For divided multi-lane highways;

$$E_2 = 14 \times 3.0 \left[\frac{C_5 D_5}{12 \times 2000} \right] \\ + 19.75 \times 6.0 \left[\frac{C_3 D_3}{12 \times 2000} \right]$$

H_L = adjustment for the additional cost of the wearing surface,

For two- and four-lane highways;

$$H_1 = \frac{(C_2 - C_1)}{12 \times 2000} D_1 \times \left(\frac{90}{110}\right) \times 24$$

For six-lane highways;

$$H_2 = \frac{(C_2 - C_1)}{12 \times 2000} D_1 \times \left(\frac{90}{110}\right) \times 36$$

A_L = width of shoulder subbase for an embankment slope of 6:1 (feet),

For two-lane highways;

$$A_1 = \left[22 + \frac{2(d_1 + d_2 + d_3)}{3} \right]$$

For divided multi-lane highways;

$$A_2 = \left[14.375 + \frac{(d_1 + d_2 + d_3)}{3} \right]$$

B_L = adjusted width of shoulder subbase when subdrains are provided (feet),

For two-lane highways;

$$B_1 = 5.0$$

For divided multi-lane highways;

$$B_2 = 5.875$$

M_L = cost of subdrain when used under median shoulder only (dollars per longitudinal foot),

For two-lane highways;

$$M_1 = 0.0$$

For divided multi-lane highways;

$$M_2 = 1.1 (0.075 C_6 + C_7)$$

N = cost of subdrains under both shoulders (dollars per longitudinal foot),

For all highways;

$$N = 2 \times 1.1 (0.075 C_6 + C_7)$$

Y_f = adjustment for the amount of subbase material replaced by the shoulder surface and base (dollars per longitudinal foot), and

For two-lane highways;

$$Y_1 = \frac{253 \times C_4}{12 \times 27}$$

For divided multi-lane highways;

$$Y_2 = \frac{162 \times C_4}{12 \times 27}$$

Z_f = adjustment for the amount of subbase material added above the level of the pavement subbase under the shoulders.

For two-lane highways;

$$Z_1 = \frac{50 \times C_4}{12 \times 27}$$

For divided multi-lane highways;

$$Z_2 = \frac{60 \times C_4}{12 \times 27}$$

Thus, the objective of this optimal selection of flexible pavement components is to minimize the total cost of the pavement system. The various material and layer notations of the design model are graphically described in the figures which illustrate the design sections.

To quantify the boundary conditions to which the optimal design of the flexible pavement components is subject, the following constraint equations are necessary to complete the realism of this design model.

1. The selection of layer thicknesses must satisfy the structural number requirement,

$$a_1 d_1 + a_2 d_2 + a_3 d_3 + a_4 d_4 \geq SN$$

where a_i = coefficient of relative strength of material 'i'

and

SN = structural number for design.

The coefficients of relative strength are presented in Table 1 for the four pavement materials used in this design model.

2. The total thickness of the flexible pavement must be at least equal to the minimum thickness which is required by an influencing environmental consideration,

$$d_1 + d_2 + d_3 + d_4 \geq T_{\min}$$

where $T_{\min}$ = total minimum thickness of flexible pavement to satisfy environmental conditions.

The remaining constraining equations are required to account for the physical limitations inherent in the construction of the various layers of a flexible pavement. The following seven relationships complete the mathematical representation of the concept for the optimal selection of flexible pavement components.

Table 1

PAVEMENT MATERIAL SPECIFICATIONS

Material Notation	Material Description	Coefficient of Relative Strength (a_1)
d_1	Bituminous surface	0.44
d_2	Stabilized base	0.24
d_3	Compacted aggregate base	0.14
d_4	Granular subbase	0.08

3. The bituminous surface course of a primary highway is at least 3.0 in. in thickness.

$$d_1 \geq 3.0$$

4. If a stabilized base is selected for the pavement system, the minimum thickness is 4.0 in.

$$d_2 = 0 \text{ or } \geq 4.0$$

5. If a compacted aggregate base is included in the flexible pavement, a minimum thickness of 4.0 is necessary for construction purposes.

$$d_3 = 0 \text{ or } \geq 4.0$$

6. If a granular subbase is specified from the optimal selection, at least a 4.0-in. layer is required.

$$d_4 = 0 \text{ or } \geq 4.0$$

7. Because rutting and shoving of the pavement surface may result under high load repetitions for excessive thicknesses of bituminous mixtures, the maximum thickness of the bituminous surface is 10.0 in.

$$d_1 \leq 10.0$$

8. The maximum thickness of the stabilized base is established at 10.0 in. because of large vertical deformations that may result in this base course if excessive thicknesses of bituminous mixtures are used.

$$d_2 \leq 10.0$$

9. An upper limit of 20.0 in. is set for the thickness of the granular subbase to conform with present construction practice in the State of Indiana.

$$d_4 \leq 20.0$$

In summary, the optimal design of flexible pavement components is predicated on determining that minimum-cost combination of layer thicknesses which satisfy the real and practical constraining conditions. The selection of actual in-place construction costs enhances the mathematical representation of the flexible pavement design process and provides further economies in the highway construction industry.

SOLUTION

The final step in determining the optimal design of flexible pavement sections is to obtain a solution to the design model. This solution optimizes the objective function and is subject to the set of constraining situations. The design model was programmed for solution on digital computers using FORTRAN IV language.

The optimization process is performed in two stages. In the first phase, the following nine separate arrangements of flexible pavement components are optimized by a linear programming algorithm.

1. Bituminous surface and stabilized base;
2. Bituminous surface, stabilized base, and compacted aggregate base;
3. Bituminous surface, stabilized base, and granular subbase with subbase through shoulders;
4. Bituminous surface, stabilized base, and granular subbase with subdrains;
5. Bituminous surface, stabilized base, compacted aggregate base, and granular subbase with subbase through shoulders;
6. Bituminous surface, stabilized base, compacted aggregate base, and granular subbase with subdrains;
7. Bituminous surface and compacted aggregate base;
8. Bituminous surface, compacted aggregate base, and granular subbase with subbase through shoulders; and
9. Bituminous surface, compacted aggregate base, and granular subbase with subdrains.

Six of these nine layered combinations of pavement components represent all possible flexible pavement systems for the cross-sections with subbase (S_2) and for the cross-sections with subbase and subdrains under both shoulders (S_3). Only three arrangements of these components are possible for the cross-sections without subbase (S_1) and include combinations 1, 2, and 7.

The other phase of the solution involves the selection of that pavement-component arrangement which minimizes the total cost of the pavement system for the selected unit costs of the pavement materials. This final solution represents the global optimum, and no better solution exists for the specified pavement design and material cost parameters. Each flexible pavement section fulfills the design objectives for the least total cost.

DESIGN EXAMPLES

To illustrate the application of this design model, two typical examples are presented for the design of flexible pavements. In each case, the computer output provides a listing of the stipulated design data and the material specifications. After these design parameters are summarized, the optimal solution is tabulated in terms of the best design section and the required thicknesses of the pavement components. To permit a cost-effectiveness evaluation, the next two best solutions are generated for the remaining design sections. These alternate suboptimal solutions provide an economic measure of the additional cost for designs other than the optimal cross-section.

The first situation involves a two-lane highway with a primary classification. The other example is a four-lane highway with pavement material costs that differ from those corresponding values in the first illustration. The rather significant increases in flexible pavement costs are evident when the alternate suboptimal solutions are compared to the optimal solutions in the preceding two design examples.

Real economies are achieved when engineering designs are formulated to permit the selection of the optimal answer. This design model affords the highway engineer with a practical and realistic method for the optimal design of flexible pavement sections.

DESIGN OF FLEXIBLE PAVEMENT
FOR PRIMARY HIGHWAYS

DESIGN DATA

NUMBER OF LANES	2	
CBR	4.00	
AVERAGE DAILY TRAFFIC 1966	2900.	VEH./DAY
		BOTH DIRECTIONS
AVERAGE DAILY TRAFFIC 1986	5220.	VEH./DAY
		BOTH DIRECTIONS
DESIGN PERIOD	20.00	YEARS
PERCENT TRUCKS	20.00	
PERCENT MULTIPLE UNITS	25.00	
DESIGN WHEEL LOAD	10000.	LB.
REGIONAL FACTOR	1.00	
PAVEMENT TERMINAL SERVICABILITY	2.50	

MATERIALS SPECIFICATIONS

	COST	DENSITY
BITUMIN. WEARING SURFACE	10.00 \$/TON	145. LB/FT ³
BITUMINOUS SURFACE BASE	5.00 \$/TON	145. LB/FT ³
STABILIZED BASE	8.00 \$/TON	135. LB/FT ³
COMPACTED AGGREGATE BASE	3.25 \$/TON	140. LB/FT ³
GRANULAR SUBBASE	3.15 \$/YD ³	
SHOULDER SURFACE	8.50 \$/TON	145. LB/FT ³
AGGREGATE FOR SUBDRAIN	5.00 \$/YD ³	
PIPES FOR SUBDRAIN	0.70 \$/FT	

Example 1

SOLUTION

NUMBER OF LANES	2
PERCENT MULTIPLE UNITS	25.00
STRUCTURAL NUMBER	3.95
TOTAL THICKNESS	19.2 INCHES
TRUCK FACTOR	172, 18K/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	4.2 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	15.0 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 19.32 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBDRAIN

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 21.45 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THROUGH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 22.61 \$ PER LONG. FT.

Example 1 (Cont.)

SOLUTION

NUMBER OF LANES	2
PERCENT MULTIPLE UNITS	25.00
STRUCTURAL NUMBER	3.95
TOTAL THICKNESS	19.2 INCHES
TRUCK FACTOR	172.18K/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	4.2 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	15.0 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 19.32 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBDRAIN

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 21.45 \$ PER LONG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THROUGH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	6.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	9.2 INCHES

COST .. 22.61 \$ PER LONG. FT.

Example 1 (Cont.)

DESIGN OF FLEXIBLE PAVEMENT
FOR PRIMARY HIGHWAYS

DESIGN DATA

NUMBER OF LANES	4	
CBR	2.30	
AVERAGE DAILY TRAFFIC 1968	9438.	VEH./DAY
		BOTH DIRECTIONS
AVERAGE DAILY TRAFFIC 1988	17830.	VEH./DAY
		BOTH DIRECTIONS
DESIGN PERIOD	20.00	YEARS
PERCENT TRUCKS	17.00	
PERCENT MULTIPLE UNITS	50.00	
DESIGN WHEEL LOAD	10000.	LB.
REGIONAL FACTOR	1.00	
PAVEMENT TERMINAL SERVICEABILITY	2.50	

MATERIALS SPECIFICATIONS

	COST	DENSITY
BITUMEN, WEARING SURFACE	6.85 \$/TCN	145. LB/FT ³
BITUMINOUS SURFACE BASE	5.92 \$/TCN	145. LB/FT ³
STABILIZED BASE	5.53 \$/TCN	135. LB/FT ³
COMPACTED AGGREGATE BASE	2.87 \$/TCN	140. LB/FT ³
GRANULAR SUBBASE	3.33 \$/YD ³	
SHOULDER SURFACE	7.95 \$/TCN	145. LB/FT ³
AGGREGATE FOR SUBDRAIN	4.35 \$/YD ³	
PIPES FOR SUBDRAIN	0.72 \$/FT	

Example 2

SOLUTION

NUMBER OF LANES	4
PERCENT MULTIPLE UNITS	50.00
STRUCTURAL NUMBER	5.67
TOTAL THICKNESS	27.3 INCHES
TRUCK FACTOR	555, 18K/DAY

OPTIMAL SOLUTION

CROSS-SECTION WITHOUT SUBBASE

	THICKNESS
BITUMINOUS SURFACE	6.1 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	21.2 INCHES
GRANULAR SUBBASE	0. INCHES

COST .. 18.25 \$ PER LENG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBDRAIN

	THICKNESS
BITUMINOUS SURFACE	9.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	14.3 INCHES

COST .. 20.39 \$ PER LENG. FT.

ALTERNATIVE SOLUTION (SUBOPTIMAL)

CROSS-SECTION WITH SUBBASE THROUGH SHOULDER

	THICKNESS
BITUMINOUS SURFACE	9.0 INCHES
STABILIZED BASE	0. INCHES
COMPACTED AGGREGATE BASE	4.0 INCHES
GRANULAR SUBBASE	14.3 INCHES

COST .. 23.14 \$ PER LENG. FT.

Example 2 (Cont.)

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2. Buick, T. R., "Analysis and Synthesis of Highway Pavement Design," a Thesis submitted to Purdue University for the degree of Master of Science in Civil Engineering, June 1968.
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APPENDIX A
COMPUTER PROGRAM

TEST	TEST METHOD	TEST RESULTS
20X-20X COMPACTED AGGREGATE BASE	ASTM D 1557	100%
20X-20X GRANULAR SUBBASE	ASTM D 1557	100%
20X-20X SHOULDER SURFACE	ASTM D 1557	100%
20X-20X AGGREGATE FOR SUBBASE	ASTM D 1557	100%
20X-20X PAPERS FOR SUBBASE	ASTM D 1557	100%

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	52
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PART A

05/20/07

THIS SECTION IS TO ESTABLISH A VALLEY FIRM SOIL SUPPORT, SSV.

 $15.5 \text{ V} = 4.900 \text{ A} (0.12 \text{ cm})$

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1000 1000 1000

PLUMMER, S.E.

THIS SECTION IS FOR THE SOLUTION OF THE EQUIVARIANT ION-PAIR LEAD APPLICATIONS DURING THE LIFE TIME OF THE PAVEMENT.

10

```

ACTAD=ACTE1+AUT2C1/*0.0
IF INL=CC-2) TL=1.0
IF INL=CC-4) TL=0.9
IF INL=CC-6) TL=0.8
GO 2000 III=1.5
IF III=CC-1) GO 10 6
IF III=CC-2) PERMU=PERMU/2.0
IF III=CC-3) PERMU=PERMU*3.0
IF PERMU=CC-100-C) PERMU=100.0
IF AUTAD=PERTHREE TL=1.0 PERMU=0.9*110C-C+PERMU*0.1171/10000.0
GO IFD=35.0

```

.....

PART C

patients

THIS SECTION IS FOR THE SOLUTION OF THE STRUCTURAL NUMBER.

COMPTON-ALLEN, 1981

5461.0

1001 5M+1.0

$$(QW)=9.36\text{eALOG}_{10}(SN)=-0.27\text{eALOG}_{10}(COP)/(CO-1.5)/(CO-0.40+10\%) / 5\% +$$

 $-15.19 \pm 0.37756\text{e}^{(5V-3.0)/-0.97\text{eALOG}_{10}(R)}$

1001 31 03 14M03.37.14B14
14 1401.14.1401 14 1401

2001 31 05 14:00:30.301M03111
FREQ1.0E+001 60 10 1002

 $5 \times 5 \text{ M} = 0.1$

Equation 1

15. 1910. 377561559-1.01-0.97%AL0.01C(HF)
IF1047-GE-COMP1 CO TC 1002

```

100) 5N=5N+C.GI
      IF(EQ.2,LE,COMP) GO TO 1003
      EQ=3+9.36*ALOG10(5N)-0.20*ALOG10(100-M)/(10.40+109N+.75**
      15.19)+0.375*155V-3.01-0.97*ALOG10(M)
      IF(EQ.3,LE,COMP) GO TO 1003
      IF(EQ.3,GE,COMP) GO TO 1004
      1004) 4121=5N-1.0
C .....
C .....
C PART D
C .....
C PURPOSE
C .....
C THIS SECTION IS FOR DETERMINING THE TOTAL THICKNESS OF PAVEMENT.
C
      IF(OW,LE,9CCO.3) GO TO B
      IF(OW,GE,1CCO.3) GO TO A
      B) 4131=.723*41.037/CB**1.05-45.180*EXP(-CB)
      GO TO 10
      A) 4131=.423*52.736/CB**0.90-16.88*EXP(-CB)
      GO TO 10
      10) CONTINUE
C
      WRITE(6,2CC) NL,PERML,PI21,B131,TF
      200) FORMAT(1D15.15X,8P,SOLUTION,///
      120X,3A,NUMBER OF LANES ..... 38.12,1
      120X,3A,PERCENT MULTIPLE UNITS ..... 45.2,1
      120X,3A,STRUCTURAL NUMBER ..... 45.2,1
      120X,3A,TOTAL THICKNESS ..... 45.1,80 INCHES,1
      120X,3A,TRUCK FACTOR ..... 46.0,80 LBK/DAY,1 28)
C .....
C .....
C PART E
C .....
C PURPOSE
C .....
C THIS SECTION SELECTS THE OPTIMAL PAVEMENT, BY THE MODIFIED LINEAR
C PROGRAMMING ALGORITHM.
C
      IF(ML,EG.2) GO TO 1
      IF(ML,EG.4) GO TO 2
      IF(ML,EG.6) GO TO 3
C
C 2 LANES
C
      1) C11=1CK11+DEN11/24000.0)*24.0
      C12=1CK12+DEN12/24000.0)*24.0
      C13=1CK13+DEN13/24000.0)*24.0
      C14=1CK14+112.0*27.0)*24.0
      C15=1CK15+DEN15/24000.0)*20.0)*3.0
      C16=1CK16+DEN16/24000.0)*31.0)*6.0
      C17=1C.075*CK16+CK17)*1.1*2.0
      C18=1CK18+112.0*27.0)*258.0
      C19=1CK19+112.0*27.0)*1122.0)*1130.666)

```

79 80

83 84

86

MAIN - EFN SOURCE STATEMENT - IFALS - DECODED

C1101=0.0
C111=ICK1A1/112.0*27.011*90.C
C112=ICK1A1/112.0*27.011*90.C
C113=ICK1A1-CR111/112.0*2000.01*DEH111*190.0/110.01*24.0
GO TO 12

C
C 4 LINES

2 C111=ICK111*DEH111/24000.01*24.0
C112=ICK121*DEH121/24000.01*24.0
C113=ICK131*DEH131/24000.01*24.0
C14=ICK141/112.0*27.011*90.C
C15=ICK151*DEH151/24000.01*14.0*3.0
C16=ICK161*DEH161/24000.01*19.75*6.C
C17=10.075*CK161*CK171*1.1
C18=ICK1A1/112.0*27.011*162.0
C19=ICK1A1/112.0*27.011*114.375*8131*0.3331
C1101=10.075*CK161*CK171*1.1
C111=ICK1A1/112.0*27.011*60.C
C112=ICK1A1/112.0*27.011*9.875
C113=ICK1A1-CR111/112.0*2000.01*DEH111*190.0/110.01*24.0
GO TO 12

C
C 6 LINES

3 C111=ICK111*DEH111/24000.01*36.0
C112=ICK121*DEH121/24000.01*36.0
C113=ICK131*DEH131/24000.01*36.0
C14=ICK141/112.0*27.011*36.0
C15=ICK151*DEH151/24000.01*14.0*3.0
C16=ICK161*DEH161/24000.01*19.75*6.C
C17=10.075*CK161*CK171*1.1
C18=ICK1A1/112.0*27.011*162.0
C19=ICK1A1/112.0*27.011*114.375*8131*0.3331
C1101=10.075*CK161*CK171*1.1
C111=ICK1A1/112.0*27.011*60.C
C112=ICK1A1/112.0*27.011*9.875
C113=ICK1A1-CR111/112.0*2000.01*DEH111*190.0/110.01*24.0
GO TO 12

12 F111=3.0
F1A1=-10.C
F1S1=4.0

IFB111-11-20.01 GO TO 22
IFB111-GE-20.11 GO TO 21
21 Y1A1=11*CCOD.0
GO TO 122

C
C SUBPROBLEM 1 - SECTION WITH NO SUBBASE

C
C CASE 1

22 A=6
A=2

R161=-10.0
C111=0.11
C121=0.121*1.041
C131=0.0

```

C(1)=0.0
C=GI(1)+G(1)+G(13)
CO 121 J=1.6
CO 121 K=1.2
121 A(1,K)=A(1,J,K)
CALL MINITIA,NROW,B,C,D,P,N,O,S,PSCL,DSOL,MEAN)
VA(1,1)=PSCL(1)
VA(2,1)=PSCL(2)
VA(3,1)=0.C
VA(4,1)=0.C
VA(5,1)=5
C
C CASE 2
C
122 P=5
A=2
C(1)=G(1)
C(2)=G(3)+1.041
C(3)=0.0
C(4)=0.0
C=GI(1)+G(1)+G(13)
CO 221 J=1.5
CO 221 K=1.2
221 A(1,K)=A(1,J,K)
CALL MINITIA,NROW,B,C,D,P,N,O,S,PSCL,DSOL,MEAN)
VA(1,2)=PSCL(1)
VA(2,2)=0.C
VA(3,2)=PSCL(2)
VA(4,2)=0.C
VA(5,2)=5
C
C CASE 3
C
P=7
A=3
R(1)=10.0
R(2)=5.0
C(1)=G(1)
C(2)=G(2)+1.041
C(3)=G(3)+1.083
C(4)=0.0
C=GI(1)+G(1)+G(13)
CO 321 J=1.7
CO 321 K=1.3
321 A(1,K)=A(1,J,K)
CALL MINITIA,NROW,B,C,D,P,N,O,S,PSCL,DSOL,MEAN)
VA(1,3)=PSCL(1)
VA(2,3)=PSCL(2)
VA(3,3)=PSCL(3)
VA(4,3)=0.C
VA(5,3)=5
C
55111=AMIN1(VA(5,1),VA(5,2),VA(5,3))
CO 123 J=1.3
IF(VA(5,1).LE.55111) IP=1
IF(VA(5,1).LE.55111) GO TO 1123

```

122

134

149

```

123 CONTINUE
1123 CO 2123 KK=1.5
      YB(KK,1)=VA(RN,1P)
2123 CONTINUE
C SUPRCBLEM 11. SECTION WITH SUBDRAIN
C
C CASE 4
C

```

```

      P=8
      N=3
      R161=-10.0
      R171=4.0
      R181=-20.0
      C111=G111+G112
      C121=G121+1.041+G112
      C131=G141+G112
      C141=0.0
      C=619)*G161+G171+G110)-G111)+G113)
      CO 421 J=1.8
      CO 421 K=1.3

```

```

421 R1J,K)=A31J,K)
      CALL MINITIA,NROW,B,C,C,P,N,0.5,PSCL,DSOL,MEAN)
      VA11,A1=PSCL(1)
      VA12,A1=PSCL(2)
      VA13,A1=0.0
      VA14,A1=PSCL(3)
      VA15,A1=5

```

180

```

C CASE 5
C

```

```

      P=7
      N=3
      R161=4.0
      R171=-20.0
      C111=G111+G112
      C121=G131+1.041+G112
      C131=G141+G112
      C141=0.0
      C=619)*G161+G171+G110)-G111)+G113)
      CO 521 J=1.7
      CO 521 K=1.3

```

```

521 R1J,K)=A61J,K)
      CALL MINITIA,NROW,B,C,C,P,N,0.5,PSCL,DSOL,MEAN)
      VA11,S1=PSCL(1)
      VA12,S1=0.0
      VA13,S1=PSCL(2)
      VA14,S1=PSCL(3)
      VA15,S1=5

```

193

```

C CASE 6
C

```

```

      P=9
      N=4
      R161=-10.0
      R171=4.0

```

TIME 02.420

DATE 08/06/69

MAIN - EFN SOURCE STATEMENT - IFN(5) -

```

R(9)=4.0
R(9)=20.0
C(1)=G(1)+G(12)
C(2)=G(2)+G(1)+G(12)
C(3)=G(3)+G(1)+G(12)
C(4)=G(4)+G(12)
C=G(5)+G(6)+G(7)+G(10)+G(11)+G(13)
CO 621 J=1,9
CO 621 K=1,6

```

```

621 A(I,J,K)=A(I,J,K)
CALL MINIT(A,NROW,B,C,D,M,N,O,S,PSCL,DSOL,KEAN)
VAL(1,1)=PSOL(1)
VAL(2,1)=PSOL(2)
VAL(3,1)=PSOL(3)
VAL(4,1)=PSOL(4)
VAL(5,1)=5

```

206

```

C
SS(12)=AMIN1(VAL(5,4),VAL(5,5),VAL(5,6))
CO 456 I=4,6
IF VAL(5,1).LE.SS(12)) IR=1
IF VAL(5,1).LE.SS(12)) GO TO 1456
456 CONTINUE
1456 CO 2456 KK=1,5
V(1,KK,7)=VAL(KK,1K)
2456 CONTINUE

```

```

C
C SUPPLEMENT 111, SECTION WITH SUBBASE THRU SHOULDER
C
C CASE 7
C

```

```

P=8
N=3
R(6)=10.0
R(7)=4.0
R(8)=20.0
C(1)=G(1)+G(9)
C(2)=G(2)+G(1)+G(9)
C(3)=G(3)+G(9)
C(4)=0.0
C=G(5)+G(6)+G(10)+G(11)+G(13)
CO 721 J=1,8
CO 721 K=1,3

```

```

721 A(I,J,K)=A(I,J,K)
CALL MINIT(A,NROW,B,C,D,M,N,O,S,PSCL,DSOL,KEAN)
VAL(1,7)=PSOL(1)
VAL(2,7)=PSOL(2)
VAL(3,7)=0.0
VAL(4,7)=PSOL(3)
VAL(5,7)=5

```

237

```

C
C CASE B
C
P=7
N=3
R(6)=4.0
R(7)=20.0

```

```

C(1)=G(1)+G(9)
C(2)=G(1)+1.0+G(9)
C(3)=G(1)+G(9)
C(4)=0.0
C=G(5)+G(6)+G(10)+G(8)+G(13)
CO 821 J=1.7
CO 821 K=1.3
821 ATJ,K)=ATJ,K)
CALL MINITIA,NODM,B,C,U,M,N,O,S,PSCL,DSOL,REBA)
VA(1,8)=PSOL(1)
VA(2,8)=0.0
VA(3,8)=PSOL(2)
VA(4,8)=PSOL(3)
VA(5,8)=5

C
C CASE 9
C
P=9
N=4
R(6)=10.0
R(7)=4.0
R(8)=4.0
R(9)=20.0
C(1)=G(1)+G(9)
C(2)=G(2)+1.0+G(9)
C(3)=G(3)+1.0+G(9)
C(4)=G(4)+G(9)
C=G(5)+G(6)+G(10)+G(8)+G(13)
CO 921 J=1.9
CO 921 K=1.4
921 ATJ,K)=ATJ,K)
CALL MINITIA,NODM,B,C,U,M,N,O,S,PSCL,DSOL,REBA)
VA(1,9)=PSOL(1)
VA(2,9)=PSOL(2)
VA(3,9)=PSOL(3)
VA(4,9)=PSOL(4)
VA(5,9)=5

C
S(13)=MIN(VA(5,7),VA(5,8),VA(5,9))
CO 789 J=7.9
IF(VA(5,1)-LE-S(13)) IN=1
IF(VA(5,1)-LE-S(13)) GO TO 1789
789 CONTINUE
1789 CO 2789 KK=1.5
VB(KK,3)=VA(KK,1N)
2789 CONTINUE
C
300 FORMAT(ABX,9THICKNESS,7
120X,26HBITUMINOUS SURFACE .... ,P5.1,7H INCHES,7
120X,26HSTABILIZED BASE ..... ,P5.1,7H INCHES,7
120X,26HCOMPACTED AGGREGATE BASE ,P5.1,7H INCHES,7
120X,26HGRANULAR SUBBASE ..... ,P5.1,7H INCHES,77
136X,10HCOST .. ,P6.2,16H $ PER LONG. FT.,777777)
SOPT=AMIN1(S(13),S(12),S(13))
CO 75 NI=1.3
IF(S(1N1)-LE-SOPT) GO TO 25

```

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MAIN - EFN SOURCE STATEMENT - IFN(S) -

DCC40CD

```
75 CONTINUE
25 IF(NT.LE.1) GO TO 325
IF(NT.LE.2) GO TO 625
IF(NT.LE.3) GO TO 925

C
C
325 WRITE(6,400)
400 FORMAT(15X,16OPTIMAL SOLUTION,///
120X,29HCROSS-SECTION WITHOUT SUBBASE,/)
WRITE(6,300) (YB(KK,1),KK=1,5)
IF(SS1(2).LE.SS1(3)) GO TO 329
GO TO 330
329 WRITE(6,800)
800 FORMAT(15X,33ALTERNATIVE SOLUTION (SUBOPTIMAL),///
120X,27HCROSS-SECTION WITH SUBDRAIN,/)
WRITE(6,300) (YB(KK,2),KK=1,5)
WRITE(6,500)
500 FORMAT(15X,33ALTERNATIVE SOLUTION (SUBOPTIMAL),///
120X,43HCROSS-SECTION WITH SUBBASE THROUGH SHOULDER,/)
WRITE(6,300) (YB(KK,3),KK=1,5)
GO TO 2000
330 WRITE(6,500)
WRITE(6,300) (YB(KK,3),KK=1,5)
WRITE(6,800)
WRITE(6,300) (YB(KK,2),KK=1,5)
GO TO 2000

C
C
625 WRITE(6,600)
600 FORMAT(15X,16OPTIMAL SOLUTION,///
120X,27HCROSS-SECTION WITH SUBDRAIN,/)
WRITE(6,300) (YB(KK,2),KK=1,5)
IF(SS1(1).LE.SS1(3)) GO TO 628
GO TO 630
628 WRITE(6,700)
700 FORMAT(15X,33ALTERNATIVE SOLUTION (SUBOPTIMAL),///
120X,29HCROSS-SECTION WITHOUT SUBBASE,/)
WRITE(6,300) (YB(KK,1),KK=1,5)
WRITE(6,500)
WRITE(6,300) (YB(KK,3),KK=1,5)
GO TO 2000
630 WRITE(6,500)
WRITE(6,300) (YB(KK,3),KK=1,5)
WRITE(6,700)
WRITE(6,300) (YB(KK,1),KK=1,5)
GO TO 2000

C
C
925 WRITE(6,900)
900 FORMAT(15X,16OPTIMAL SOLUTION,///
120X,43HCROSS-SECTION WITH SUBBASE THROUGH SHOULDER,/)
WRITE(6,300) (YB(KK,3),KK=1,5)
IF(SS1(1).LE.SS1(2)) GO TO 929
GO TO 930
929 WRITE(6,700)
WRITE(6,300) (YB(KK,1),KK=1,5)
```



```

MINX      - EFN  SOURCE STATEMENT - IPNISI -
DURING COMPUTATION.
THE LAST NE ROWS OF A CORRESPOND TO THE EQUALITY.
CONSTRAINTS OF THE PROBLEM
- M-VECTOR OF REQUIREMENTS.
- N-VECTOR OF COSTS.
- A-CONSTANT ADDED TO THE OBJECTIVE FUNCTION.
- NUMBER OF CONSTRAINTS-INEQUALITIES AND EQUALITIES.
- ROWS OF A1.
- NUMBER OF VARIABLES. ICCLPMAS OF A1.
- NUMBER OF EQUALITY CONSTRAINTS. THE LAST NE ROWS
  OF A.
- VALUE OF THE OBJECTIVE FUNCTION.
- IPNISI-VECTOR, PRIMAL SOLUTION. PSOLIN+11,....
  PSOLIN+P) ARE SLACK VARIABLES FOR THE PRIMAL
  PROBLEM.
- IPNISI-VECTOR, DUAL SOLUTION. DSOLIN-NE+11,....
  DSOLIN+M) ARE SURPLUS VARIABLES FOR THE DUAL
  PROBLEM.
- DESCRIBES THE OUTCOME OF THE LP ALGORITHM
- KENN+2 INDICATES THAT THE PRIMAL OBJECTIVE
  FUNCTION IS UNBOUNDED. THE DUAL PROBLEM HAS AN
  FEASIBLE SOLUTION.
- KENN+1 INDICATES THAT THE DUAL OBJECTIVE
  FUNCTION IS UNBOUNDED. THE PRIMAL PROBLEM HAS AN
  FEASIBLE SOLUTION.
- KENN+1 INDICATES THAT AN OPTIMAL FEASIBLE SOLUTION
  HAS BEEN FOUND AND STORED IN PSOL, DSOL, AND S.
- KENN+1 INDICATES THAT THERE IS NO SOLUTION.

```

REMARKS

```

THE CURRENT DIMENSION STATEMENT IS ADEQUATE FOR M-LE-50+
AND N-LE-50. IF THE USER WISHES TO CHANGE THE DIMENSION
STATEMENT TO SUIT HIS NEEDS, THE FOLLOWING FORM SHOULD BE
USED.
DIMENSION AIM+1,P+M-NE+11,BIP+1,C(N),PSCLIM+M1,DSOLIM+M1
LOCAL ARRAYS.
DIMENSION INDIM+M-NE+11,INDIM+11,ICNIM+11,THMINIM+M-NE+11,
  IMINIM+M-NE+11,JMAX(P+1),DELMAX(P+1)
THE USER SHOULD CHECK TO SEE THAT THE DIMENSION STATEMENT
OF MINIT AGREES WITH THE DIMENSION STATEMENT OF THE CALLING
PROGRAM.

```

METHOD

```

THE MINIT METHOD IS A MODIFICATION OF THE COMPOSITE SIMPLEX
METHOD. THE ALGORITHM WAS DEVELOPED BY ROBERT LLEWELLYN AND
IS PRESENTED IN:
LLEWELLYN, R.W., "LINEAR PROGRAMMING", HOLT, RINEHART AND
WINSTON, NEW YORK, 1964, PP. 207-227.
THE ALGORITHM WAS PROGRAMMED IN ALGOL BY RODOLFO C. SALAZAR
AND SUBRATA K. SEN, CARNEGIE INSTITUTE OF TECHNOLOGY,
GRADUATE SCHOOL OF INDUSTRIAL ADMINISTRATION, PITTSBURGH, PA.

```

INITIALIZATION

MINX

```

LCOL=M*N-NE+1
LCCL=LCOL-1
CO 10 I=1,M
NEM=M+2-1
A(NEW1,LCOL)=B(NEW1-1)
CO 10 J=1,N
A(NEW1,J)=A(NEW1-1,J)
10 CONTINUE
CO 20 J=1,N
A(1,J)=C(J)
20 CONTINUE
M=M+1
N1=N+1
N(NEW1)=M-NE

```

```

IF (M .EQ. NE) GO TO 31
CO 30 I=1,M1
CO 30 J=N1,NMNE
A(1,J)=0.0
IF (J .EQ. N+1-1) A(1,J)=1.0

```

```

30 CONTINUE
31 CONTINUE
A(1,LCCL)=0
IF (NE .LE. 0) GO TO 37
CO 36 I=1,NE
NEM=M-NE+1+1
IF (B(NEW1) .LE. C-0) GO TO 36
A(NEW1)=B(NEW1)
CO 35 J=1,N
35 A(NEW1,J)=A(NEW1,J)
36 CONTINUE
37 CONTINUE
TD=1.0E-8

```

```

C      TD IS SET EQUAL TO A VERY SMALL NUMBER. THE CONDITION OF
C      OPTIMALITY IS THE NON-NEGATIVITY OF A(1,J) FOR J=1,...,LCCL-1,
C      AND OF A(1,LCCL) FOR I=2,...,M+1. IF THE A(1,J) VALUES ARE
C      GREATER THAN OR EQUAL TO -TD THEY ARE CONSIDERED TO BE
C      NON-NEGATIVE
C

```

```

CO 50 I=2,M1
50 ICHK(1)=0
PNE1=M-NE+1
CO 55 I=2,PNE1
55 ICHK(1)=N+1-1
IF (NE .EQ. 0) GO TO 200

```

```

C      IF THERE ARE ANY EQUALITY CONSTRAINTS IN THE PROBLEM, THE
C      PROGRAM FIRST GOES TO PHASE1, OTHERWISE IT GOES DIRECTLY TO
C      THE MAIN ALGORITHM
C

```

```

C      PHASE1
C      APPLIED ONLY TO EQUALITY CONSTRAINTS
C

```

```

14=1
100 CONTINUE

```

```

111R.CY.NE) GO TO 155
CMIN=L.OE+6
C
C      GMIN IS SET EQUAL TO A LARGE NUMBER FOR INITIALIZATION PURPOSES
C
      L=1
      CO 110 J=1,N
      THMIN(J)=1.OE+6
      IF (ALL,J) 109,110,111C
109 INCL1=J
      L=L+1
110 CONTINUE
      IF (L-1) 120,120,130
120 CO 125 J=1,N
125 INCL2=J
      L=L+1
130 CONTINUE
      LM1=L-1
      PNE2=M-NE+2
      CO 160 K=1,L,M1
      JK=INDIRJ
      CO 150 I=PNE2,M1
      IF (CHK(I)) 150,148,150C
146 IF (ALL,JK) 150,150,147
147 THETA=ATN(L.COL/ATN(JK))
148 THMIN(JK)=THETA
149 INCL3=J
      L=L+1
150 CONTINUE
      CAPMA=THMIN(JK)*ATN(JK)
      IF (GAPMA-CMIN) 155,160C,160
155 GMIN=GAPMA
      JMIN=JK
160 CONTINUE
      TM=THMIN(JMIN)
      IS=IM
      IF=JMIN
      ASSIGN 190 TO NTRANS
      CO TO 3000
190 CONTINUE
      IM=IR+1
      CO TO 100
195 CONTINUE
C
C      END OF PHASE1
C
200 CONTINUE
C
C      MAIN ALGORITHM
C
      L=1
      K=1
      CO 210 J=1,L.COL1
      IF (ALL,J) 209,210,210
209 INCL1=J
      L=L+1

```

MINX - EFN SOURCE STATEMENT - (FNIS) -

C 1ND KEEPS TRACK OF THE COLUMNS IN WHICH A(I,J) IS NEGATIVE

C 210 CONTINUE

C 220 I=2,M1

C IF (A(I,LCOL)+TD) 215,22C,220

C 215 INDI(I)=I

C 220 CONTINUE

C 220 CONTINUE

C 1ND1 KEEPS TRACK OF THE ROWS IN WHICH A(I,LCOL) IS NEGATIVE

C 225 IF (I-1) 229,225,229

C 226 IF (K-1) 226,400,226

C 227 CO 228 J=1,LCOL

C 228 J=1,LCOL

C 229 INDI(I)=J

C 230 IF (A(I,J)+TD) 231,232,232

C 232 CONTINUE

C PRIMAL PROBLEM HAS NO FEASIBLE SOLUTION, DUAL OBJECTIVE
FUNCTION IS UNBOUNDED

C 235 RETURN

C 236 CONTINUE

C 237 IF (I-1) 240,230,240

C 238 IF (K-1) 500,231,500

C 239 CO 232 I=2,M1

C 240 INDI(I)=J

C 241 IF (A(I,J)+TD) 242,232,242

C 242 CONTINUE

C PRIMAL OBJECTIVE FUNCTION IS UNBOUNDED, DUAL PROBLEM HAS NO
FEASIBLE SOLUTION

C 245 RETURN

C 246 CONTINUE

C 247 IF (K-1) 500,400,500

C 248 ASSIGN 302 TO NPH1

C 249 GO TO 2000

C 250 CONTINUE

C 251 IS=IMAX

C 252 IF=JM

C 253 ASSIGN 200 TO NTRANS

C 254 GO TO 3000

C 255 ASSIGN 401 TO NGAP

C 256 GO TO 1000

C 257 CONTINUE

C 258 IS=IM

C 259 IF=JMIN

C 260 ASSIGN 200 TO NTRANS

C 261 GO TO 3000

C 262 ASSIGN 501 TO NGAP

C 263 GO TO 1000

C 264 ASSIGN 502 TO NPH1

MINX - EFN SOURCE STATEMENT - IFN(5) -

DECLARED

```

GO TO 2000
502 CONTINUE
IF (GMIN-1.0E+6) 602,601,602
601 IS=IMAX
IF=JM
ASSIGN 200 TO NTRANS
GO TO 3000
602 IF (PHIMAX+1.0E+6) 604,603,604
603 IS=IM
IF=JMIN
ASSIGN 200 TO NTRANS
GO TO 3000
604 IF (ABS(PHIMAX)-ABS(GMIN)) 605,605,606
605 IS=IM
IF=JMIN
ASSIGN 200 TO NTRANS
GO TO 3000
606 IS=IMAX
IF=JM
ASSIGN 200 TO NTRANS
GO TO 3000
1000 CONTINUE
C
C      BEGIN PROGRAMMA
C
C      CMIN=1.0E+6
C
C      CMIN IS SET EQUAL TO A LARGE NUMBER FOR INITIALIZATION PURPOSES
C
C      JMIN=0
C      LONE=L-1
C      GO TO 20 L1=1,LONE
C      INCL=INDL11
C      THMIN=INDL11=0
C      THMIN(INCL11)=1.0E+6
C      GO TO 1010 L1=L1+1
C      IF (1-NCT-(TA11+INDL11)-CT-TD3-AND(TA11+LCC11-CL1-TD11)) GO TO 1010
C      THETA=ATN(LCC11/TA11,INDL11)
C      IF (1-NCT-(THETA-AT-THMIN(INCL11))) GO TO 1010
C      THMIN(INCL11)=THETA
C      THMIN(INCL11)=1
C      1010 CONTINUE
C      GAMMA=1.0E+6
C      IF (THMIN(INCL11)-NE-1.0E+6) GAMMA=THMIN(INCL11)+ATN(INDL11)
C      IF (GAMMA-GE-6MIN) GO TO 1020
C      CMIN=GAMMA
C      JMIN=INDL11
C      1020 CONTINUE
C      IF (JMIN-CT-0) IM=JMIN(JMIN)
C      GO TO NGAM,(INDL1,501)
C
C      END OF PROGRAMMA
C
C      2000 CONTINUE
C
C      BEGIN PROPHI

```


MINX - EFN SOURCE STATEMENT - IFN(15) -

```

C PHIMAX=-1.0E+6
C
C PHIMAX IS SET EQUAL TO A SMALL NUMBER FOR INITIALIZATION
C PURPOSES
C
      IMAX=0
      KONE=K-1
      GO 2020 A1=1,KONE
      INDIR1=INDIR1
      JMAX=INDIR1+1
      CELMAX=INDIR1-1.0E+6
      GO 2010 J=1,LCOL
      IF (1.NGT.(I(INDIR1,J).LT.-TD).AND.(A11,J).GE.-TE))) GO TO 2010
      CELTA=A11,J)/A11INDIR1,J)
      IF (1.NGT.(CELTA.GT.0ELPMAX(INDIR1))) GO TO 201C
      CELMAX=INDIR1-DELTA
      JMAX=INDIR1+J
2010 CONTINUE
      PHI=-1.0E+6
      IF (0ELPMAX(INDIR1).NE.-1.0E+6) PHI=0ELPMAX(INDIR1)+A11INDIR1,LCCL1
      IF (PHI.LE. PHIMAX) GO TO 2020
      PHIMAX=PHI
      IMAX=INDIR1
2020 CONTINUE
      IF (11MAX.GT. 0) J=JMAX(1MAX)
      GO TO APM1,(302,502)
C
C      END OF PROPH1
C
C 3000 CONTINUE
C
C      BEGIN ROWTRANS(15,17)
C      PERFORM THE USUAL PIVOT OPERATION WITH A115,17) AS PIVOT
C      ELEMENT
C
      IF (115.NE. 0).AND.117.NE. 0) GO TO 3010
      KEN=1
C
C      NO SOLUTION
C
      RETURN
3010 CONTINUE
      CUPMY=A115,17)
      GO 3030 J=1,LCOL
3030 A115,J)=A115,J)/CUPMY
      GO 3050 I=1,M1
      IF (1.EQ.15) GO TO 3050
      IF (A11,17).EQ.0.0) GO TO 3050
      CUPMY=A11,17)
      GO 3040 J=1,LCOL
3040 A11,J)=A11,J)-A115,J)*CUPMY
3050 CONTINUE
      ICHK(15)=17
      GO TO NTRANS,(200,190)
C

```

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DC040CD - IFN(S) -

MINK - EFN

SOURCE STATEMENT

```

C      END OF MONTRANS
C      4000 CONTINUE
C      BEGIN RESULTS
C      S=A11,LCOL
C      PN=M+N
C      4010 I=1,MN
C      PSOL(I)=0.0
C      4010 CSOL(I)=0.0
C      FIND PRIMAL SOLUTION VECTOR
C      4020 I=2,M1
C      ICHK(I)=ICHR(I)
C      4020 PSOL(ICHK(I))=A11,LCOL
C      4030 J=N1,LCOL1
C      JN=J-N
C      4030 CSOL(JN)=A11,J
C      4040 J=1,N
C      JN=J-LCOL1-N
C      4040 CSOL(JN)=A11,J
C      MEAN=0
C      RETURN
C      END
C      50DATA
C      EXECUTION

```

APPENDIX B

INPUT DATA INSTRUCTIONS

The input data is summarized on two computer cards. The value of the parameters are to be assigned by the designing engineer using the algorithm; they include soil and traffic characteristics, planning period, environmental factors and materials cost and densities.

Card 1

The first Card has twelve parameters.

Parameter	Formst	Symbol	Description
1	I2	NL	Number of lanes; 2,4, or 6
2	F7.2	CBR	CBR value of the subgrade
3	F7.0	ADT ₁	Initial daily traffic in both directions
4	F7.0	ADT ₂	Terminal daily traffic in both directions
5	F7.2	DP	Design period of pavement
6	F7.2	TR	Percentage of trucks in traffic stream
7	F7.2	CT	Percentage of combination trucks in truck streams
8	F7.0	DWL	Design Wheel load 9 Kips or 10 Kips
9	F7.2	RF	Regional Factor
10	F7.2	P	Pavement terminal serviceability
11	I5		Estimated Construction year
12	I5		Estimated pavement retirement year

Card 2

The second card has twelve parameters.

Parameter	Format	Symbol	Description
1	F7.2	C ₁	Unit cost of bituminous surface, \$/Ton
2	F7.2	C ₂	Unit cost of stabilized base, \$/Ton
3	F7.2	C ₃	Unit cost of compacted aggregate base, \$/Ton
4	F7.2	C ₄	Unit cost of granular subbase, \$/YD ³
5	F7.2	C ₅	Unit cost of shoulder surface, \$/ton
6	F7.2	C ₆	Unit cost of subdrain fill, \$/YD ³
7	F7.2	C ₇	Unit cost of subdrain pipe, \$/Ft
8	F7.2	C ₈	Unit cost of wearing surface course, \$/Ton
9	F7.2	D ₁	Density of bituminous surface, lb/ft ³
10	F7.2	D ₂	Density of stabilized base, lb/ft ³
11	F7.2	D ₃	Density of compacted aggregate base, lb/ft ³
12	F7.2	D ₄	Density of shoulder surface, lb/ft ³