

A SYSTEMS APPROACH TO THE FLEXIBLE PAVEMENT DESIGN PROBLEM

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.



## CHAPTER 1 - INTRODUCTION

This report stems from research performed in Project 2-8-62-32, "Application of AASHO Road Test Results to Texas Conditions." Its purpose is to make available to the Texas Highway Department a recommended procedure for the design of flexible pavements. The procedure takes into account both physical and cost variables, and provides a means for making design decisions based on probable overall costs, rather than on initial construction costs alone.

Physical variables are treated in terms of how they affect the serviceability-time curve of the pavement. Means for evaluating them in any given locality are presented.

Cost variables considered are the following: initial construction, routine maintenance, periodic seal coating, overlay construction, user costs due to traffic delays during overlay construction, and salvage value. All future costs, discounted to present value, are added to initial construction costs to form the overall cost.

Because of the number of variables involved, and the need to investigate all possible designs meeting selected criteria, initial attempts to prepare the usual curves or nomograms for the designer's use were quickly abandoned. The solution of the design equations, and the search for the least-cost design, are made in a computer. The computer program, and a brief description of what it contains, are included in this report.

In writing the computer program, the attempt was made to provide for ease of change, so that as new findings are made in flexible pavement

research, they can be incorporated into the program with a minimum of effort. Meanwhile, the program is recommended as an aid not only to the design engineer but also to the research engineer in establishing where emphasis should be placed in pavement research.

In order to shorten the report for the convenience of the design engineer, to whom it is addressed, practically all supporting data and documentation have been excluded: these will be treated in later reports.

## CHAPTER 2 - PHYSICAL VARIABLES

There is a large group of physical variables associated with materials, construction, traffic and environment that affect pavement performance. Of these, a few have been quantified and their effect on pavement performance has been established, at least approximately. This chapter defines the physical variables of the latter group considered in this design method, and describes, qualitatively, their effect on pavement performance.

## 2.1 Design Variables

The sketch in Figure 1 represents a pavement composed of  $n$  layers above the subgrade level. The material in each of these layers, and in the foundation layer, is characterized by a strength coefficient,  $a_i$ , where the subscript,  $i$ , identifies the position of the layer in the structure. Layers are numbered consecutively from the top downward; thus,  $i = 1$  for the surfacing layer, and  $i = n + 1$  for the foundation layer, which is considered to be of infinite thickness. The thickness of any layer above the foundation is represented by the symbol,  $D_i$ .

Measured in situ values of the strength coefficient,  $a$ , range from about 0.17 for a wet clay to about 1.00 for a strongly stabilized base material. No way has been found for predicting these values with suitable accuracy from laboratory tests. For the present the strength coefficient of a material proposed for use in a new pavement in a particular locality must be estimated from deflection measurements made on the same type of material in an existing pavement located in the same general area. Details of the procedure will be given later.

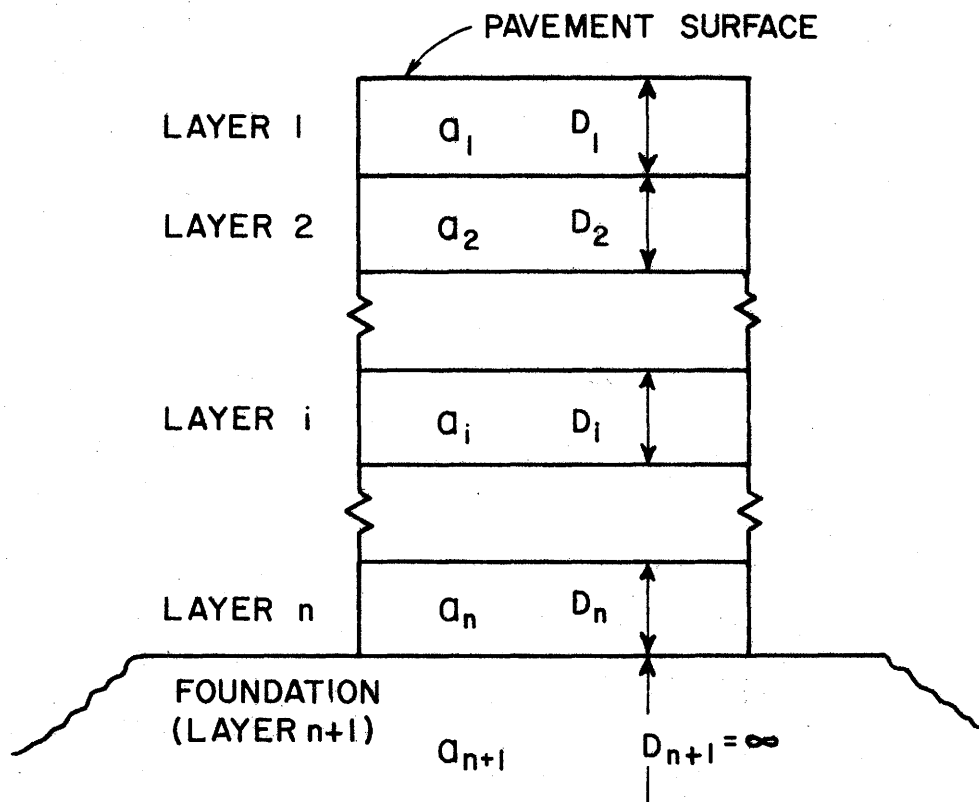


Figure 1: A pavement section of n layers above the subgrade level.

## 2.2 Deflection Variables

An important feature of this design procedure is the use of the Dynaflect\* for measuring deflections on existing highways. Descriptions of the instrument and examples of its use in pavement research have been published previously (1)(2)(3). Suffice it to say here that a dynamic load of 1000 lbs, oscillating sinusoidally with time at 8 cps, is applied through two steel load wheels to the pavement, as indicated in Figure 2. Five sensors, resting on the pavement at the numbered points shown in the figure, register the vertical amplitude of the motion at those points in thousandths of an inch (or mils).

A deflection basin of the type illustrated in Figure 3 results from the Dynaflect loading. The symbol  $W_1$  represents the amplitude--or deflection--occurring at Point 1,  $W_2$  is the deflection at Point 2, etc.

A deflection variable important to this design procedure is the surface curvature index,  $S$ , shown in Figure 3 and defined by the equation,  $S = W_1 - W_2$ . The value of  $S$  for a proposed design can be predicted with reasonable accuracy from the deflection equation to be given in a later chapter, provided that the values of the design variables are known. Two designs are assumed to be physically equivalent if they have the same value of  $S$ , and the same swelling clay parameters. (Swelling clay parameters are discussed in a later section). Of two designs with differing values of  $S$ , but with the same swelling clay parameters, the design with the lower value of  $S$  is assumed to be the better (longer lived).

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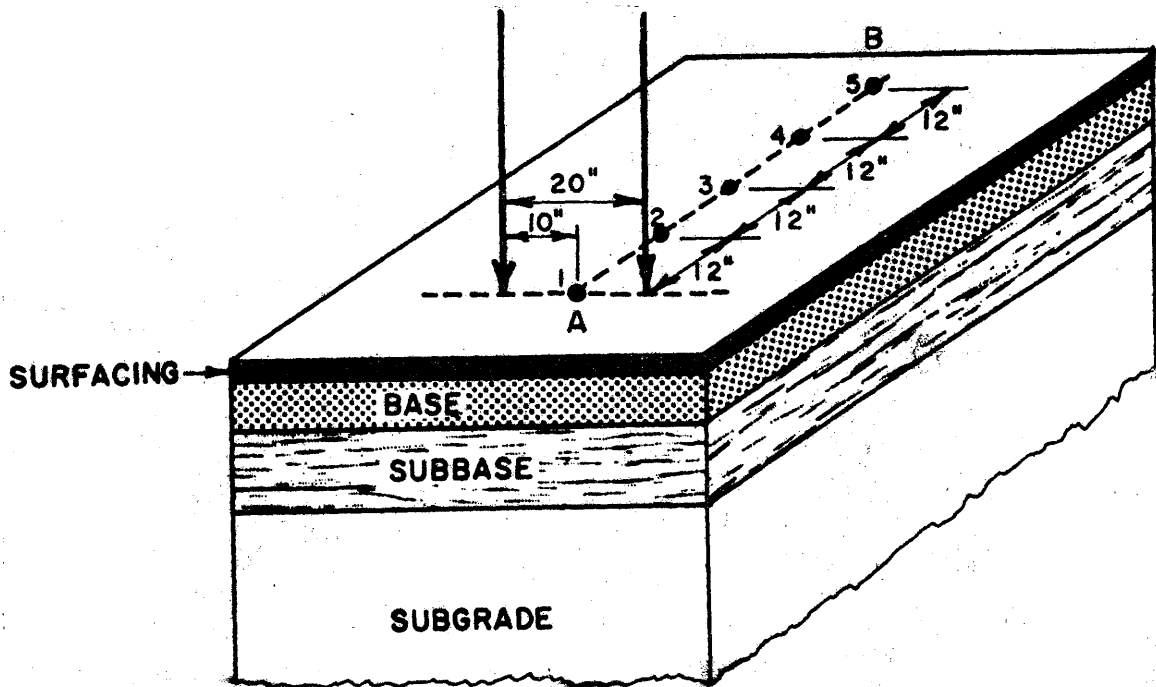


Figure 2: Position of Dynaflect sensors and load wheels during test. Vertical arrows represent load wheels. Points numbered 1 through 5 indicate location of sensors.

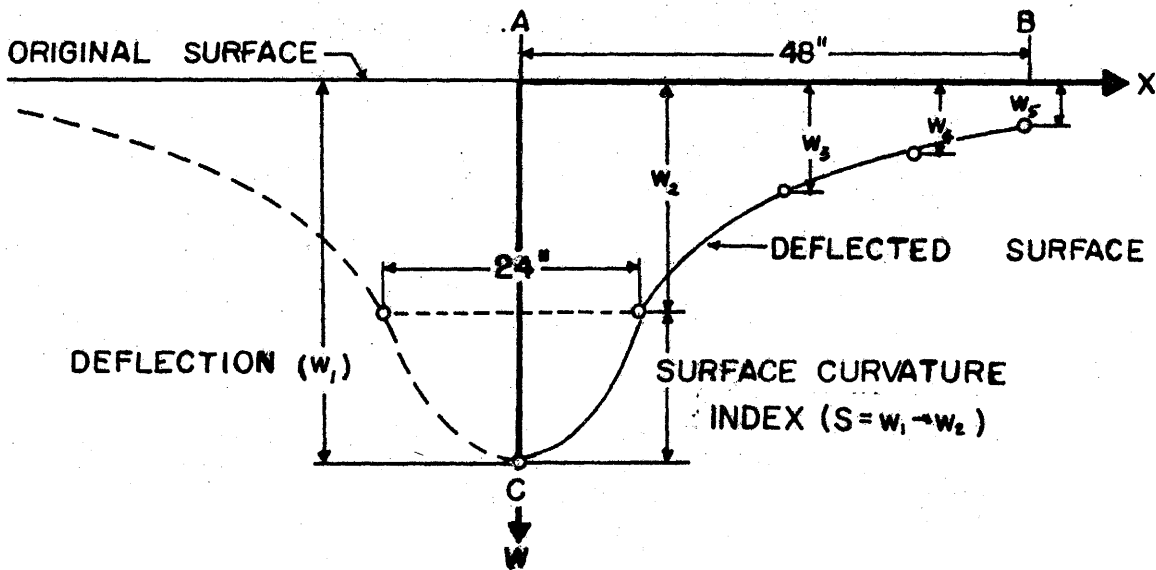


Figure 3: Typical deflection basin reconstructed from Dynaflect readings. Only half of basin is measured. S is the deflection variable used to represent the design.

### 2.3 Traffic Variables

In describing traffic, it is first necessary to select the total period of time following construction that is of interest to the design engineer. This is usually in the order of 20 to 40 years, and is termed the analysis period; its length is represented by the symbol, C. Definitions of the other traffic variables follow.

$t$  = time, years.  $t = 0$  at the time of initial construction.

$r_0$  = the ADT, in one direction, when  $t = 0$ .

$r_c$  = the ADT, in one direction, when  $t = C$ .

$N$  = the total number of equivalent applications of an 18-kip single axle load (computed by the standard AASHO method) that will have passed over the pavement in one direction at any time,  $t$ .

$N_c = N$  at  $t = C$ .

It is assumed that the design engineer can obtain the values of  $r_0$ ,  $r_c$  and  $N_c$  from the Planning Survey Division of the Highway Department for any particular location. The relationship between  $N$  and  $t$  will be given in a later chapter, and will be referred to as the traffic equation. Typical plots of  $N$  versus  $t$  for light, moderate and heavy traffic are shown in Figure 4.

An assumption made with regard to traffic on multi-lane highways is that commercial vehicles use the outer lane.



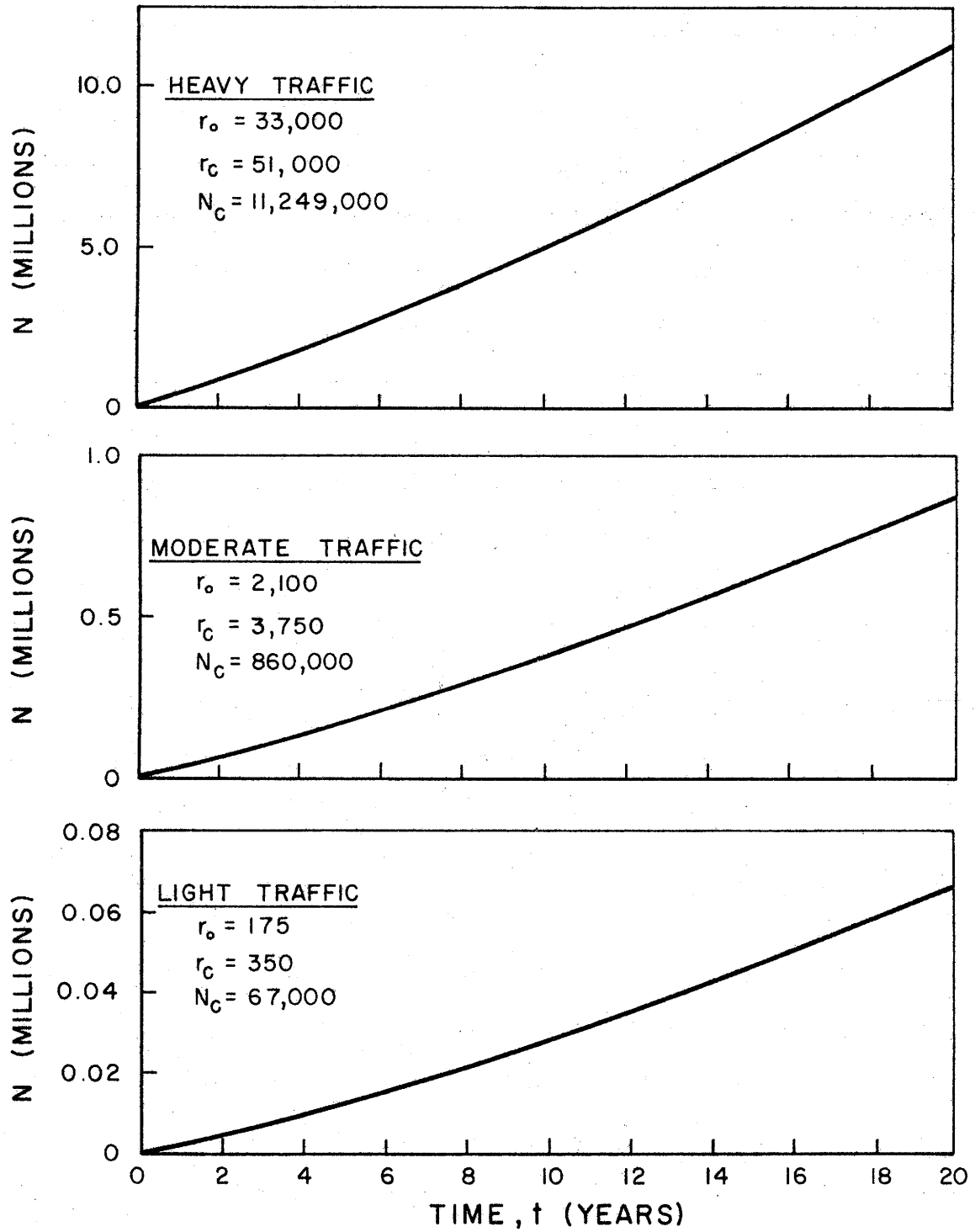


Figure 4: Typical traffic curves.

## 2.4 Performance Variables

The serviceability index (P) versus time (t) curve for a pavement is referred to as the performance curve of the pavement. A performance variable is any variable describing, or in any way affecting, the performance curve. Obviously the design, deflection and traffic variables discussed above are also performance variables.

Figure 5 is a computed performance curve for a flexible pavement to which two overlays have been applied within an analysis period of 20 years. A performance period is defined as the time, in years, from the completion of initial or overlay construction, when  $P = P_1$ , to the time when the serviceability index next reaches a predetermined value,  $P_2$ . Performance periods are numbered in chronological order, Period 1 being the first.

Except in the computation of user costs due to traffic delays--to be discussed later in the report--the time required to construct an overlay is neglected. The value of t at the end of the  $k^{\text{th}}$  period, or at the beginning of the next period, is represented by the symbol,  $t_k$ .

An important phenomenon affecting the performance curve is that of uneven volumetric expansion and contraction of materials in the foundation. This effect is illustrated in Figure 6, which portrays the computed serviceability history of four pavements constructed on foundation materials of four different types. These performance curves represent pavements not subjected to traffic: only the effect of foundation movements is shown.

In the case of the three lower curves in Figure 6 the variable, P, approaches an ultimate value,  $P_2'$ , taken here as 1.5. The variable,  $b_1$ ,

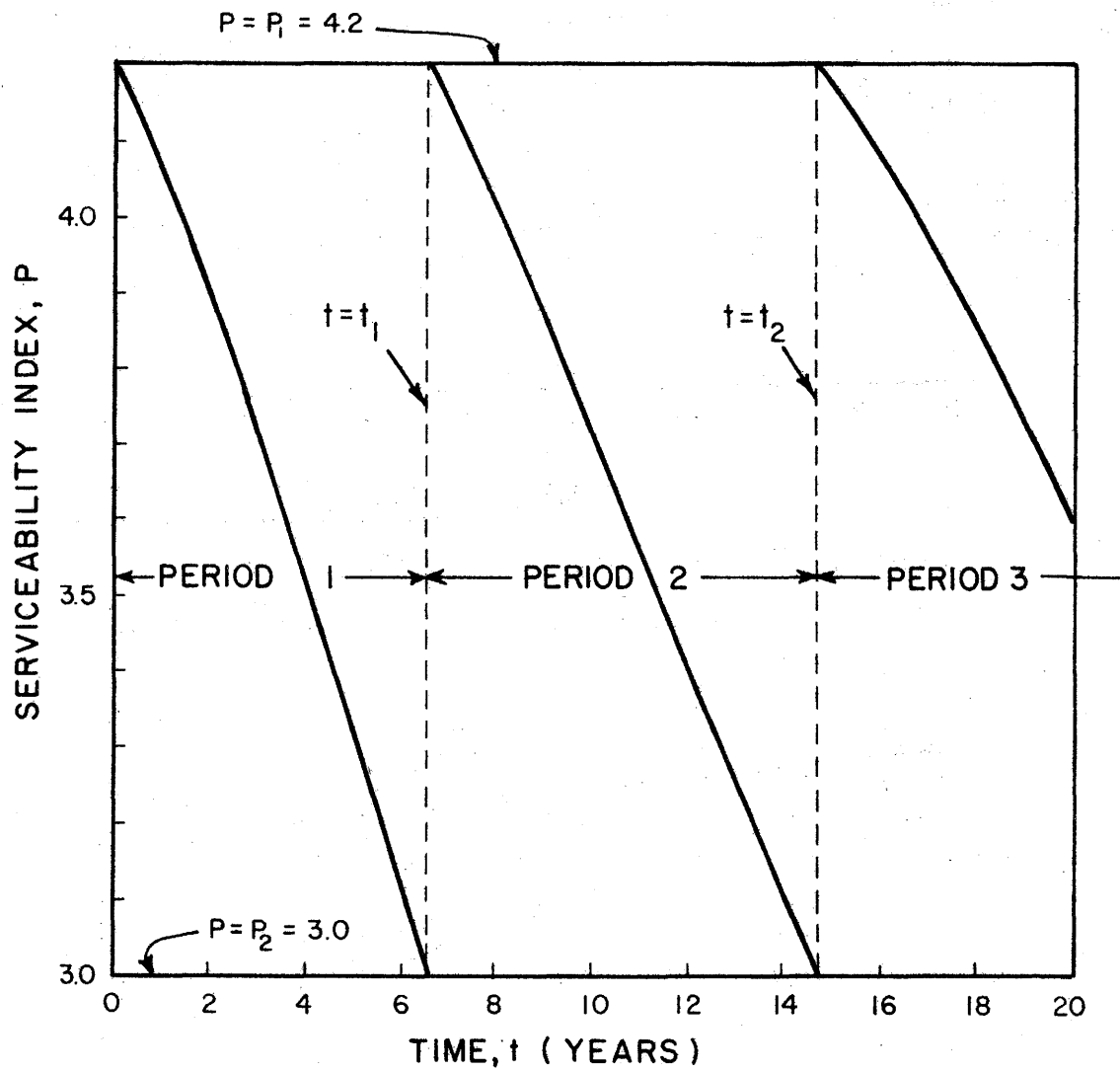


Figure 5: A performance curve for an analysis period of 20 years involving two overlays constructed at  $t = t_1$  and  $t = t_2$ , and three performance periods.

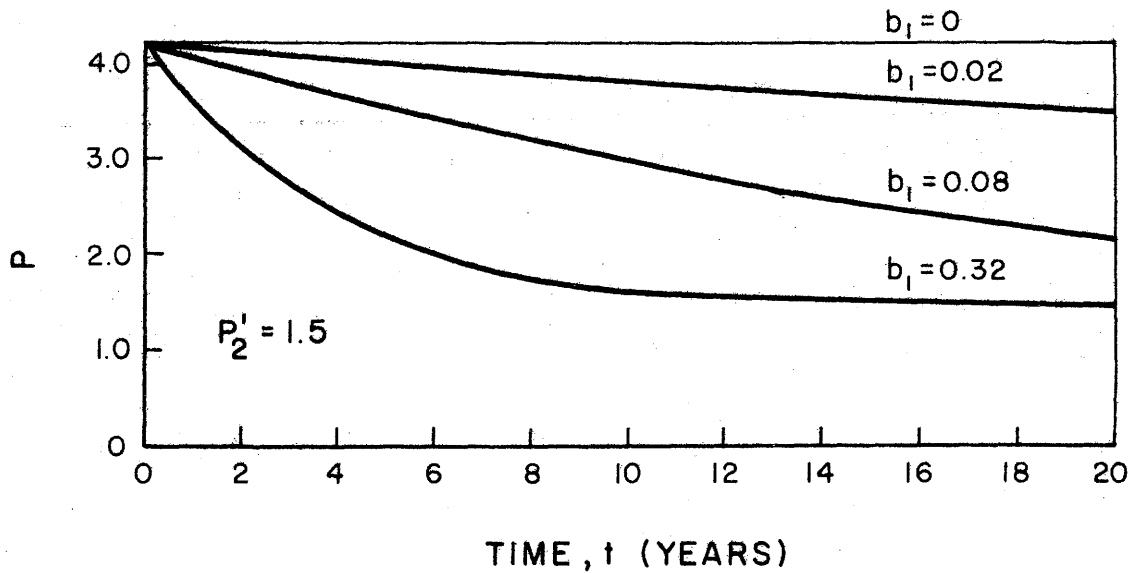


Figure 6: Four performance curves illustrating the effect of foundation movements in the absence of traffic. These curves approach an assumed lower limit of  $P = 1.5$ .

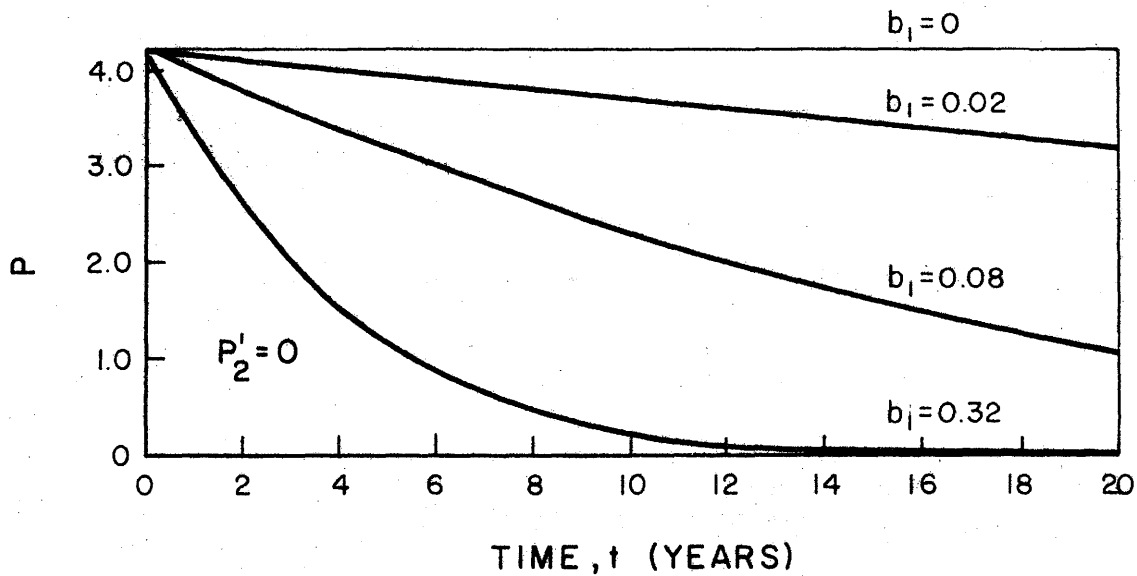


Figure 7: Same as Figure 6, but the curves here have a lower limit of  $P = 0$ .

represents the relative rate at which P approaches its ultimate value. Thus, the curve labeled " $b_1 = .02$ " approaches the 1.5 serviceability level much more slowly than the curve labelled " $b_1 = .32$ ."

Not much is known about the quantity  $P_2'$ , since the relevant serviceability index data are not available. The ultimate value of P in the absence of traffic may be greater or less than the value of 1.5 used in Figure 6. For comparison with Figure 6, performance curves in the absence of traffic for  $P_2' = 0$  are shown in Figure 7.

If  $P_2'$  is fixed at an assumed value,  $b_1$  can be estimated from serviceability index data on new pavements which have not been opened to traffic but nevertheless have roughened due to swelling clays. Very limited data of this type have indicated an upper limit of approximately 0.3 for  $b_1$  when  $P_2'$  is assumed to be zero. The theoretical lower limit of  $b_1$  is zero, for any value assigned to  $P_2'$ .

No data being available for estimating  $P_2'$ , a value of zero has been assumed for the present.

In the development of a relationship between performance variables based on AASHO Road Test data, it was necessary to define a serviceability loss function, Q, as follows:

$$Q = \sqrt{5 - P} - \sqrt{5 - P_1}$$

where P and  $P_1$  are as previously defined, and the constant, 5, is the theoretical upper limit of P. With  $P_1$  fixed (a commonly used value is 4.2), Q increases as the serviceability index, P, decreases, as shown in Figure 8. In this figure we have replotted one of the performance curves given in Figure 7, and have also plotted the corresponding curve

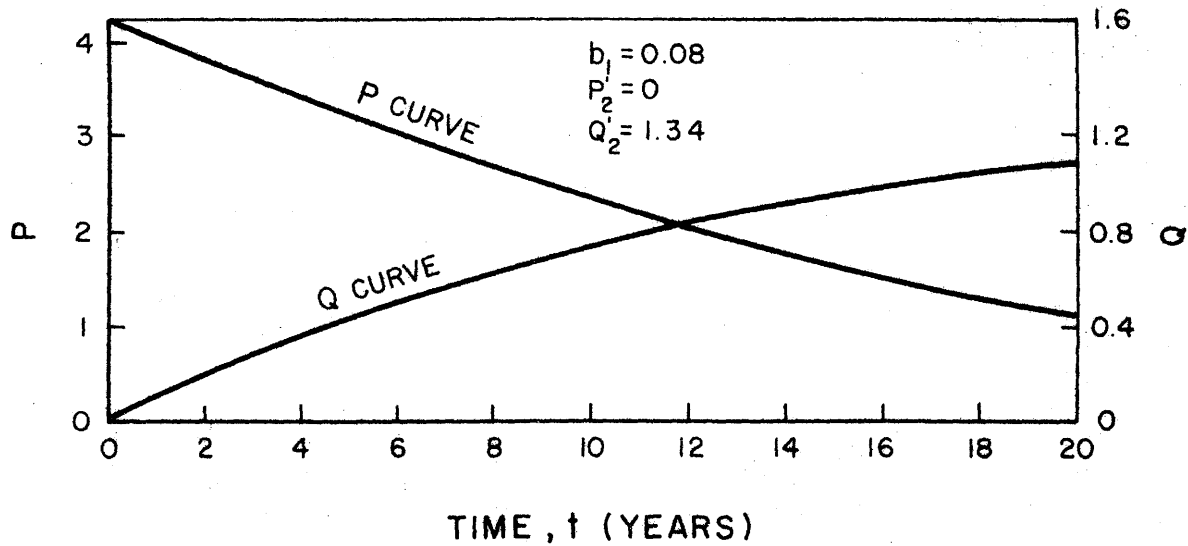


Figure 8: A performance curve and its corresponding serviceability loss curve, with no traffic operating.

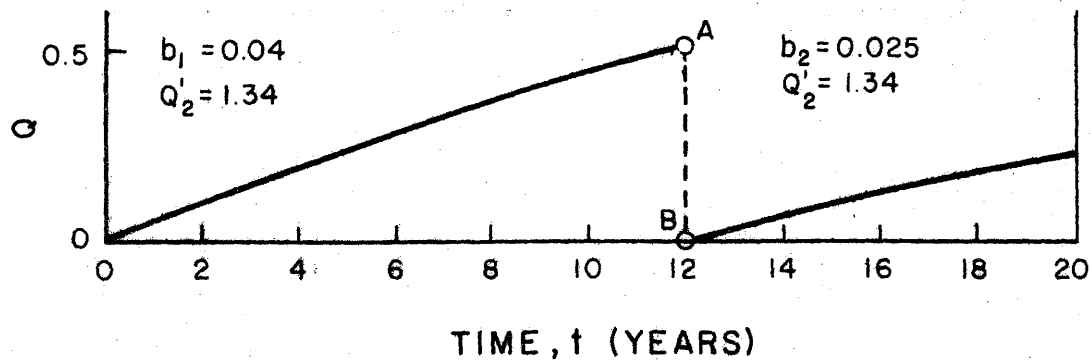


Figure 9: The assumed effect on the serviceability loss curve of the construction of an overlay at Point A. The slope of the curve at A and B is the same; both branches approach the same asymptote.

for Q. We refer to the Q versus t curve as the serviceability loss curve, to distinguish it from the P versus t curve already defined as the performance curve. The P and Q curves approach ultimate values of zero and 1.34 respectively ( $P_2' = 0$ ,  $Q_2' = 1.34$ ).

As previously indicated the serviceability loss or Q-curve of Figure 8 is taken to represent a pavement which has carried no traffic. It was necessary to form an hypothesis as to how the placement of an overlay would affect such a Q-curve. The hypothesis adopted was simply this: (1) the slope of the curve at  $t = t_k$  is the same before and after placement of an overlay, and (2) the ultimate value,  $P_2'$ , of the serviceability index remains unchanged. The graph shown in Figure 9, wherein the slope of the Q-curve is the same at points A and B, illustrates this hypothesis.

The adoption of the hypothesis requires the computation of a new value of b at the beginning of each performance period, based on the value applicable to the preceding period. Thus, for the Q-curve shown in Figure 9, the value of  $b_1$  assigned to the first period is .04, while the computed value of  $b_2$  applying to the second period is .025. Both branches of this Q-curve would, if extended, approach an ultimate value of 1.34 ( $Q_2' = 1.34$ ) corresponding to  $P_2' = 0$ .

One other performance variable must be mentioned, a daily temperature constant,  $\alpha$ , and its effective value over one year,  $\bar{\alpha}$ . This variable arose during an analysis of the AASHO Road Test data, and is believed to represent an increased susceptibility of asphaltic concrete to cracking under traffic in cold weather. The daily constant,  $\alpha$ , is defined as the average of the maximum and minimum daily temperature, less 32°F. The change in the loss

function,  $Q$ , occurring as the result of one day's traffic depends in part on the value of  $\alpha$  for that day. By summing the daily changes in  $Q$ , a single equivalent value of  $\alpha$ , designated  $\bar{\alpha}$ , can be used to estimate the change in  $Q$  for a full year.

For use in the computer program a value of  $\bar{\alpha}$  has been computed for each District, based on mean values of the high and low daily temperatures averaged over a ten year period. Values are given in Table 1.

It can be seen from Table 1 that the District values of  $\bar{\alpha}$  vary from a minimum of  $9^\circ$  in District 4 to a maximum of  $38^\circ$  in District 21. Figure 10 illustrates the effect of  $\bar{\alpha}$  on the performance curve.

The performance equation relating the variables discussed in this section, and the effect on the computed performance curve of the design and traffic variables, will be discussed later in the report.



TABLE 1 - DISTRICT TEMPERATURE CONSTANTS

Dist.	Temp. Const. ( $\bar{\alpha}$ )	Dist.	Temp. Const. ( $\bar{\alpha}$ )	Dist.	Temp. Const. ( $\bar{\alpha}$ )	Dist.	Temp. Const. ( $\bar{\alpha}$ )	Dist.	Temp. Const. ( $\bar{\alpha}$ )
1	21	6	23	11	28	16	36	21	38
2	22	7	26	12	33	17	30	22	31
3	22	8	26	13	33	18	26	23	25
4	9	9	28	14	31	19	25	24	24
5	16	10	24	15	31	20	32	25	19

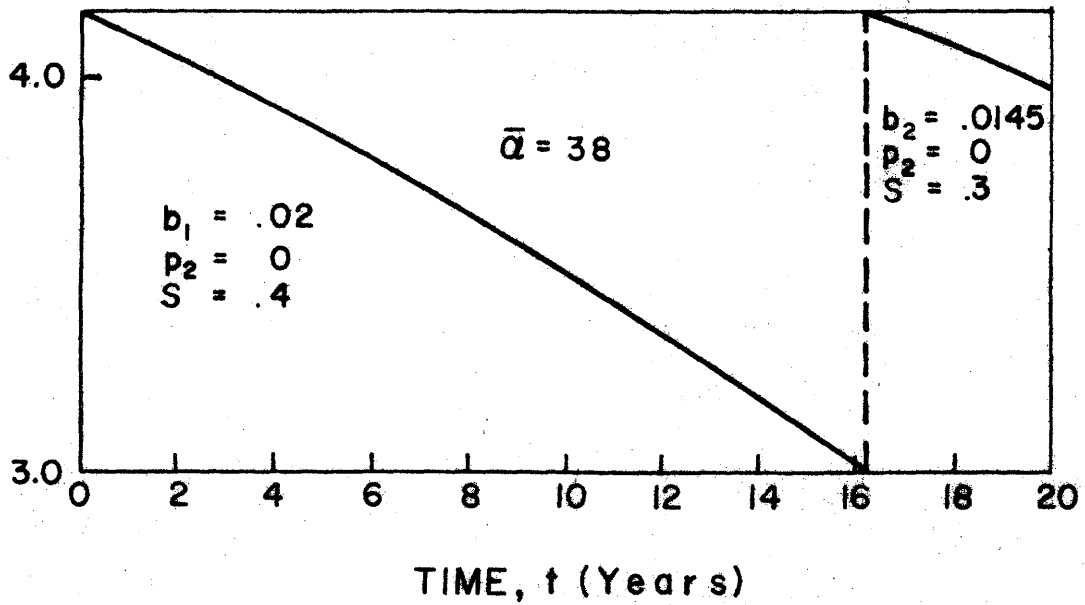
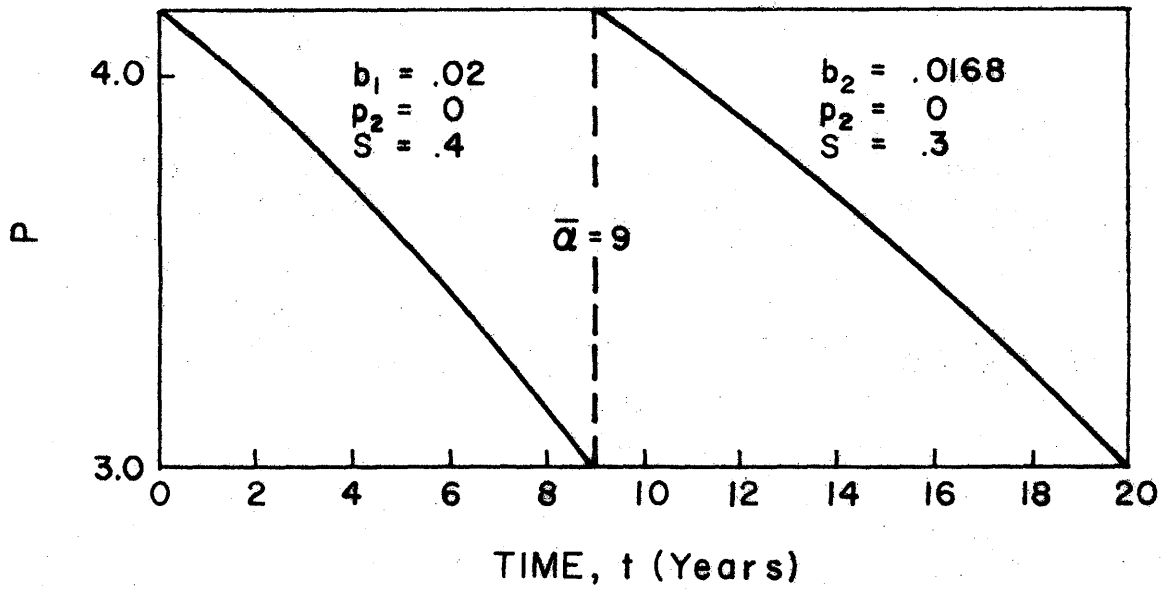


Figure 10: Performance periods are lengthened by an increase in  $\alpha$ , as illustrated here for the extreme values in Texas.

## 2.5 Summary of Definitions of Physical Variables

For the convenience of the reader in examining the equations to be given in the next chapter, we repeat below, in a more concise form, the definitions previously given. Also included in the list are a few additional symbols not previously defined but appearing in the equations.

### Design Variables -

$a_i$  = the strength coefficient of the  $i^{\text{th}}$  layer of a pavement,  
 $i = 1, 2, \dots, n + 1$ .

$D_i$  = the thickness of the  $i^{\text{th}}$  layer in inches.  $D_{n+1} = \infty$ .

### Deflection Variables -

$W_j$  = the deflection sensed by the  $j^{\text{th}}$  sensor of the Dynaflect.

$r_j$  = distance, in inches, from the point of application of either Dynaflect load, to the  $j^{\text{th}}$  sensor.  $r_1^2 = 100$ .

$r_2^2 = 244$ .

### Traffic Variables -

$t$  = time (years) since initial construction.

$N$  = total number of equivalent applications of an 18-kip axle that will have been applied in one direction during the time,  $t$ .  $N$  is expressed in millions.

$C$  = length in years of the analysis period.

$N_c = N$  when  $t = C$ .

$N_k = N$  when  $t = t_k$  (defined below).

$r_0 = \text{ADT (one direction) when } t = 0$ .

$r_c = \text{ADT (one direction) when } t = C$ .

Performance Variables -

$P$  = the serviceability index at time,  $t$ .

$P_1$  = the expected maximum value of  $P$ , occurring only immediately after initial or overlay construction.

$P_2$  = the specified value of  $P$  at which an overlay will be applied.

$P_2'$ , a swelling clay parameter = the assumed value of  $P$  at  $t = \infty$ , in the absence of traffic. In general,  $0 \leq P_2' \leq P_1$ .

$b_k$  is a swelling clay parameter applying to the  $k^{\text{th}}$  performance period. A value between zero and 0.3 must be specified for  $b_1$ , depending on the expected activity of foundation clays.

$$b_{k+1} = b_k e^{-b_k (t_k - t_{k-1})}$$

$t_k$  = the value of  $t$  at the end of the  $k^{\text{th}}$  performance period, or the beginning of the next period.  $t_0 = 0$ .

$Q$ , the serviceability loss function =  $\sqrt{5 - P} - \sqrt{5 - P_1}$ .

$Q_2 = Q$  when  $P = P_2$ .

$$Q_2' = \frac{\sqrt{5 - P_2'}}{\sqrt{5 - P_1}}$$

$\alpha$ , a daily temperature constant =  $1/2$  (maximum daily temperature + minimum daily temperature) -  $32^\circ\text{F}$ .

$\bar{\alpha}$  = the effective value of  $\alpha$  for a typical year in a given locality, defined by the formula for the harmonic mean--

$$\bar{\alpha} = \frac{n}{\sum_{i=1}^n \left( \frac{1}{\alpha_i} \right)}$$

where  $n$  is the number of days in a year, and  $\alpha_i$  is the

value of  $\alpha$  for the  $i^{\text{th}}$  day of the year. To obtain an approximate value of  $\bar{\alpha}$  for this report, the formula was used with  $n = 12$ , and  $\alpha_i =$  the mean value of  $\alpha$  for the  $i^{\text{th}}$  month averaged over a ten year period.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is crucial for ensuring transparency and accountability in the organization's operations.

2. The second part of the document outlines the various methods and tools used to collect and analyze data. It highlights the need for consistent data collection procedures and the use of advanced analytical techniques to derive meaningful insights from the data.

3. The third part of the document focuses on the role of technology in data management and analysis. It discusses how modern software solutions can streamline data collection, storage, and analysis, thereby improving efficiency and accuracy.

4. The fourth part of the document addresses the challenges associated with data management, such as data quality, security, and privacy. It provides strategies to mitigate these risks and ensure that the data remains reliable and secure.

5. The fifth part of the document concludes by summarizing the key findings and recommendations. It stresses the importance of ongoing monitoring and evaluation to ensure that the data management processes remain effective and up-to-date.

CHAPTER 3 - MATHEMATICAL RELATIONSHIPS ASSUMED  
TO EXIST BETWEEN THE PHYSICAL VARIABLES

In this chapter are presented a set of empirical equations relating the physical variables previously treated. As indicated in Chapter 1, the data upon which they are based, and the procedures followed in their derivation, will be the subject of future reports.

### 3.1 Discussion of Equations

The mathematical relationships assumed to exist between the variables discussed in Chapter 2 are expressed in the form of three empirical equations-- a deflection equation, a traffic equation and a performance equation. The deflection equation relates the deflection variable  $S$  to the design variables  $a_i$  and  $D_i$ . The traffic equation relates the traffic variable  $N$  to the traffic variables  $C$ ,  $r_o$ ,  $r_c$ ,  $N_c$  and  $t$ . The performance equation relates the serviceability loss function  $Q$  to the deflection variable  $S$ , the performance variables  $\alpha$ ,  $Q_2'$  and  $b_k$ , and the traffic variables  $N$  and  $t$ . To facilitate discussion, the three equations can be written in abbreviated notation as follows:

$$\text{Deflection Equation: } S = F(a_i, D_i)$$

$$\text{Traffic Equation: } N = F(C, r_o, r_c, N_c, t)$$

$$\text{Performance Equation: } Q = F(S, \alpha, Q_2', b_k, N, t)$$

where the symbol  $F$  is read "a known function of."

To illustrate how these equations would be used to solve a simple design problem involving only physical variables, suppose that it is desired to calculate the length,  $t_1$ , of the first performance period for a pavement of known design. In addition to the design parameters  $a_i$  and  $D_i$ , values of the following quantities must be known to obtain a solution:  $C$ ,  $r_o$ ,  $r_c$ ,  $N_c$ ,  $Q_2$ ,  $Q_2'$  and  $b_1$ .

To clarify the procedure to be followed in solving this problem we rewrite the three equations as follows with the known variables underscored:

$$S = F(\underline{a_i}, \underline{D_i})$$

$$N = F(\underline{C}, \underline{r_o}, \underline{r_c}, \underline{N_c}, t_1)$$

$$\underline{Q_2} = F(S, \underline{\alpha}, \underline{Q_2'}, \underline{b_1}, N, t_1)$$



On examining the preceding equations we see at once that of the three unknowns, one of them--the variable  $S$ --can be computed directly from the first equation. The computed value of  $S$  is then substituted in the third equation. At this stage we have two equations (the second and third) involving two unknowns,  $N$  and  $t_1$ . These two equations are then solved simultaneously for  $N$  and  $t_1$ : the value of  $t_1$  so obtained is the quantity we set out to find.

The computing procedure indicated above is but one of many included in the computer program. It was used here simply to illustrate one way in which the assumed relationships between the physical variables are used in this design procedure. Further discussion of the computer program will be reserved for a later chapter.

### 3.2 The Deflection Equation

The empirical equation used in this method for estimating the surface curvature index  $S$  from the design variables  $a_i$  and  $D_i$  was developed from deflection data gathered on the A&M Pavement Test Facility located at Texas A&M University's Research Annex near Bryan. A description of the facility is contained in Research Report 32-9 (4). The equation, not previously published, is given below:

$$S = W_1 - W_2 \quad (1)$$

where

$$W_j = \sum_{k=1}^{n+1} \Delta_{jk}$$

$$\Delta_{jk} = \frac{C_0}{a_k^{c_1}} \left[ \frac{1}{r_j^2 + C_2 \left( \sum_{i=0}^{k-1} a_i D_i \right)^2} - \frac{1}{r_j^2 + C_2 \left( \sum_{i=0}^k a_i D_i \right)^2} \right]$$

$$C_0 = 0.891,$$

$$C_1 = 4.503,$$

$$C_2 = 6.25,$$

$$a_0 = D_0 = 0,$$

and the other variables are as previously defined.

The documentation of this equation will be the subject of a later report.

### 3.3 The Traffic Equation

The Traffic Equation was furnished by Mr. James Brown of the Texas Highway Department and is given below in the form used in this method.

$$N_k = \frac{N_c}{C(r_o + r_c)} \left[ 2r_o t_k + \left( \frac{r_c - r_o}{C} \right) t_k^2 \right] \quad (2)$$

where the symbols are as previously defined.

### 3.4 The Performance Equation

The empirical relationship between the performance variables used in this method was developed from AASHO Road Test data and then modified to include the swelling clay variables,  $b_k$  and  $P_2'$ , previously discussed. It is given below in the form it is used in the computer program.

$$Q_2 = \left[ \frac{53.6(N_k - N_{k-1})S^2}{\alpha} + Q_2' (1 - e^{-b_k(t_k - t_{k-1})}) \right] \quad (3)$$

where the variables are as previously defined.

The second term in the brackets was added to represent the effect of swelling clays.

This equation applies to the  $k^{\text{th}}$  performance period. Documentation of the equation will be the subject of a later report.

### 3.5 Predictions From The Equations

Using the computing procedure outlined in Section 3.1, a number of examples have been worked out and the results recorded in Tables 2 and 3 for the purpose of illustrating the predicted effect of some of the variables on performance period length.

Table 2 is concerned with a fairly heavy initial design (4" of asphaltic concrete on 20" of base material) to which successive 1-inch overlays are added as necessary. Three levels of traffic (heavy, moderate, light) and seven levels of the swelling clay parameter,  $b_1$ , are considered.

Table 3 treats a lighter design (2" of asphaltic concrete on 12" of base material) to which successive 2-inch overlays are added when required. Two levels of traffic (moderate, light) and seven levels of  $b_1$  are considered.

Each of the tables serves to illustrate the strong effect of the swelling clay parameter as it ranges from zero to 0.32. In fact, for  $b_1 > .04$  in either table, the effect of foundation movements appears to overshadow the effect of large changes in traffic.

TABLE 2: PREDICTIONS OF 20-YEAR PERFORMANCE CURVE FROM DEFLECTION, PERFORMANCE AND TRAFFIC EQUATIONS FOR A SELECTED INITIAL DESIGN, AND SUCCESSIVE ONE-INCH OVERLAYS ( $\bar{\alpha} = 25$ , other variables as shown below)

TRAFFIC (See Figure 4) for parameters)	PERFORMANCE* PERIOD NO.	DESIGN PARAMETERS					FROM DEFLECTION EQUATION: S (mils)	FROM PERFORMANCE AND TRAFFIC EQUATIONS: Elapsed Time, t (years), to End of Performance Period For $P_2' = 0$ and $b_1 =$ the value indicated						
		Strength Coefficients			Layer Thickness (in)			$b_1=0$	$b_1=.01$	$b_1=.02$	$b_1=.04$	$b_1=.08$	$b_1=.16$	$b_1=.32$
		$a_1$	$a_2$	$a_3$	$D_1$	$D_2$								
Heavy	1	.75	.60	.20	4	20	.108	20.0	20.0	14.0	9.0	5.0	3.0	1.5
	2	.75	.60	.20	5	20	.092		20.0	20.0	12.5	7.5	4.0	
	3	.75	.60	.20	6	20	.080				20.0	14.5	8.0	
	4	.75	.60	.20	7	20	.070					20.0	14.0	
	5	.75	.60	.20	8	20	.062						20.0	
								(3.61)	(2.99)	(3.83)	(3.11)	(3.37)	(3.55)	(3.41)
Moderate	1	.75	.60	.20	4	20	.108	20.0	20.0	20.0	12.0	6.0	3.0	1.5
	2	.75	.60	.20	5	20	.092			20.0	15.5	8.0	4.0	
	3	.75	.60	.20	6	20	.080				20.0	16.0	8.0	
	4	.75	.60	.20	7	20	.070					20.0	14.5	
	5	.75	.60	.20	8	20	.062						20.0	
								(4.16)	(3.66)	(3.16)	(3.69)	(3.85)	(3.83)	(3.57)
Light	1	.75	.60	.20	4	20	.108	20.0	20.0	20.0	12.0	6.0	3.0	1.5
	2	.75	.60	.20	5	20	.092			20.0	15.5	8.0	4.0	
	3	.75	.60	.20	6	20	.080				20.0	16.0	8.0	
	4	.75	.60	.20	7	20	.070					20.0	14.5	
	5	.75	.60	.20	8	20	.062						20.0	
								(4.20)	(3.70)	(3.21)	(3.70)	(3.86)	(3.84)	(3.57)

\* A performance period begins with the serviceability index, P, at 4.2 and ends either when P has dropped to 3.0, or when the end of the 20-year analysis period has been reached.

\*\* Figures in parenthesis are values of P at the end of the 20-year analysis period.

TABLE 3: PREDICTIONS OF 20-YEAR PERFORMANCE CURVE FROM DEFLECTION, PERFORMANCE AND TRAFFIC EQUATIONS FOR A SELECTED INITIAL DESIGN, AND SUCCESSIVE TWO-INCH OVERLAYS  
( $\bar{\alpha} = 25$ , other variables as shown below)

TRAFFIC (See Figure 4) for parameters)	PERFORMANCE* PERIOD NO.	DESIGN PARAMETERS					FROM DEFLECTION EQUATION: S (mils)	FROM PERFORMANCE AND TRAFFIC EQUATIONS: Elapsed Time, t (years), to End of Performance Period for $P_2' = 0$ and $b_1 =$ the value indicated						
		Strength Coefficients			Layer Thickness (in)			$b_1=0$	$b_1=.01$	$b_1=.02$	$b_1=.04$	$b_1=.08$	$b_1=.16$	$b_1=.32$
		$a_1$	$a_2$	$a_3$	$D_1$	$D_2$								
Moderate	1	.75	.60	.20	2	12	.482	20.0	16.0	12.0	8.0	5.0	3.0	1.5
	2	.75	.60	.20	4	12	.303		20.0	20.0	20.0	12.5	7.5	4.0
	3	.75	.60	.20	6	12	.199					20.0	15.0	8.0
	4	.75	.60	.20	8	12	.137						20.0	14.5
	5	.75	.60	.20	10	12	.100							20.0
								(3.25)	(4.03)	(3.71)	(3.04)	(3.45)	(3.69)	(3.17)
Light	1	.75	.60	.20	2	12	.482	20.0	20.0	20.0	12.0	6.0	3.0	1.5
	2	.75	.60	.20	4	12	.303				20.0	15.5	8.0	4.0
	3	.75	.60	.20	6	12	.199					20.0	16.0	8.0
	4	.75	.60	.20	8	12	.137						20.0	14.5
	5	.75	.60	.20	10	12	.100							20.0
								(4.14)	(3.63)	(3.12)	(3.69)	(3.69)	(3.83)	(3.57)

\* A performance period begins with the serviceability index, P, at 4.2 and ends either when P has dropped to 3.0, or when the end of the 20-year analysis period has been reached.

\*\* Figures in parenthesis are values of P at the end of the 20-year analysis period.





## CHAPTER 4 - EVALUATION OF STRENGTH COEFFICIENTS

It was mentioned in Chapter 2 that the strength coefficient of a material proposed for use in a new pavement in a particular locality must be estimated from deflection measurements made on the same type of material in an existing pavement in the same general area. This Chapter explains how the deflection equation can be used for calculating values of coefficients, and gives recommended testing procedures.

#### 4.1 Mathematical Basis for Coefficient Determinations

It has been found that the deflection equation (Equation 1, Section 3.2) can be used in conjunction with a Dynaflect test to estimate the coefficients,  $a_1$  and  $a_2$ , of a simple two-layer structure. Since such simple structures rarely exist, the following assumptions must be made when real pavements are considered: (1) all the layers above subgrade level are assumed to form one layer having a composite coefficient,  $a_1$ , and a thickness equal to the total pavement thickness; and (2) all the material below subgrade level is assumed to have a composite coefficient,  $a_2$ .

For this case the deflection equation can be written in generalized form for  $W_1$  and  $W_2$  as follows:

$$\underline{W_1} = F (\underline{a_1}, \underline{a_2}, \underline{D_1}, \underline{r_1})$$

$$\underline{W_2} = F (\underline{a_1}, \underline{a_2}, \underline{D_1}, \underline{r_2})$$

where the known quantities are underlined. Here,  $\underline{D_1}$  is the total pavement thickness at the point where the Dynaflect test is made while  $\underline{W_1}$  and  $\underline{W_2}$  are measured values of deflection. The symbols  $r_1$  and  $r_2$  have been previously defined. These two equations can be solved for the two coefficients,  $a_1$  and  $a_2$ .

If the pavement above subgrade level consists of only two layers--a surfacing and a base layer--and if the surfacing layer is relatively thin--say less than 10% of the base thickness--then the composite coefficient  $a_1$  obtained in this manner may be taken as a fair estimate of the in situ coefficient of the predominate base material. On the other hand, the value of the subgrade coefficient,  $a_2$ , is believed to be largely independent of the makeup of the pavement, and ~~thus~~ can be taken as a fair estimate of the subgrade strength regardless of the composition of the overlying layers.

#### 4.2 Procedure For Estimating The Subgrade Coefficient

The recommended procedure for estimating the coefficient of the subgrade of a proposed new pavement is given below:

1. Select an existing pavement, near the proposed new location, having a foundation similar to that of the proposed new pavement.
2. At selected test points uniformly spaced at 100 feet or more, make Dynaflect tests in the outer wheel path; two tests should be made near each test point, spaced about five feet apart.
3. At or near each test point drill a four to six-inch hole, measure material thicknesses and record descriptions of the materials encountered. Record total pavement thickness, and explore the subgrade to the depth necessary to confirm its similarity to the subgrade of the proposed new pavement.
4. Using the special computer program, "In Situ Material Coefficients From Dynaflect Data," supplied to the Texas Highway Department with this report, compute the composite pavement coefficient  $a_1$ , and the foundation coefficient  $a_2$ , for each Dynaflect test.
5. From the computer listing, select values of  $a_2$  for use in design. As a factor of safety it is recommended that the mean value of  $a_2$ , less one standard deviation, be used as the design value.

A list of typical subgrade coefficients measured in District 17 is given in Table 4.

TABLE 4 - IN SITU SUBGRADE COEFFICIENTS

## District 17

Date	County	Highway	Sec. No.	Material	Test Points	No. Tests	Coefficient			C.V. (%)
							Range	Avg.	Std. Dev.	
5-21-68	198	US 190	15	Red Sandy Clay	1-5	10	.218 - .226	.222	.003	1.4
5-21-68	21	FM 1687	2	Silty Black Clay	4	2	.222 - .225	.223	.002	0.9
5-21-68	21	FM 1687	2	Brown Clay	1-3	6	.217 - .246	.227	.008	3.5
5-21-68	21	FM 1687	2		5	2				
5-21-68	21	FM 1687	16		1-5	10				
5-21-68	26	FM 1361	5	Tan Sandy Clay	1-3	6	.219 - .242	.233	.009	3.9
5-21-68	239	SH 36	12	Black Clay	1-5	10	.231 - .245	.239	.005	2.1
5-21-68	21	FM 2818	1	Grey Sandy Clay	1-5	10	.224 - .263	.240	.010	4.2
5-21-68	21	FM 2776	4		1-5	10				
5-21-68	21	FM 974	17		1-5	10				
5-21-68	26	FM 1361	5	Brown Sandy Clay	4-5	4	.238 - .248	.241	.005	2.1
5-21-68	21	FM 1687	3	Sand and Clay	2 & 5	4	.253 - .264	.258	.006	2.3
5-21-68	21	FM 1687	3	Grey and Brown Sand	1	2	.255 - .263	.259	.003	1.2
5-21-68	21	FM 1687	3	Grey and Brown Sand	3-4	4				

#### 4.3 Procedure for Estimating the Coefficient of a Base Material

The recommended procedure for estimating the coefficient of a material to be used as the second layer (base) of a proposed pavement is given below:

1. Select an existing pavement located in the general area of the proposed pavement, and having (a) a relatively thin surfacing material, (b) a base similar to the material proposed for the new pavement, and (c) no subbase.
- 2,3. Test and drill the pavement as described in Steps 2 and 3 of Section 4.2.
4. Compute coefficients as in Step 4 of Section 4.2.
5. From the computer listing select values of  $a_1$  for use in design. As a factor of safety it is recommended that the mean value of  $a_1$ , less one standard deviation, be used as the design value.

A list of typical base coefficients measured in District 17 is given in Table 5.

TABLE 5 - IN SITU BASE MATERIAL COEFFICIENTS

## District 17

Date	County	Highway	Sec. No.	Material	Test Points	No. Tests	Coefficient			C.V. (%)
							Range	Avg.	Std.Dev.	
5-21-68	239	SH 36	12	Sandstone	1-5	10	.361 - .434	.388	.022	5.7
5-21-68	21	FM 1687	3	Red Sandy Gravel	1-5	10	.460 - .568	.514	.029	5.6
5-21-68	21	FM 1687	2	Mixture (Base & Subbase)	1-5	10	.483 - .578	.521	.028	5.4
5-21-68	26	FM 1361	5	Lime Stab. Sandstone	1-5	10	.478 - .850	.609	.149	24.5
5-21-68	21	FM 2776	4	Asphalt Stab. Gravel	1-5	10	.523 - .853	.631	.113	17.9
5-21-68	21	FM 974	17	Iron Ore Gravel	1-5	10	.594 - .857	.691	.083	12.0
5-21-68	21	FM 2818	1	Mixture (Base & Subbase)	1-5	10	.668 - .801	.708	.042	5.9
5-21-68	198	US 190	15	Cement Stab. Limestone	1-5	10	.763 - 1.029	.877	.094	10.7
5-21-68	21	FM 1687	16	Asph. Emul. Stab. Gravel	1-5	10	.820 - .940	.882	.041	4.6

#### 4.4 Estimating the Coefficient of a Subbase Material

The problem of estimating the coefficient of a material proposed for use as the subbase of a new pavement is the same as that of finding the coefficient of a base material if the material has previously been used as the base in a simple pavement structure of the kind described in Section 4.3. If it has not been so used, a coefficient will, for the present, have to be assigned to the material on the basis of engineering judgement. Meanwhile, a computer program and testing procedure for estimating the coefficients of a three-layer system is under development and should be available soon.





## CHAPTER 5 - EVALUATION OF SWELLING CLAY PARAMETERS

Until future research provides a link between laboratory swell tests and the performance curves of pavements, the designer will be compelled to rely upon experience and judgement in assigning values to the swelling clay parameters,  $P_2'$  and  $b_1$ . Meanwhile the following guide lines are offered as an aid in evaluating these parameters.

Since, as mentioned previously (Section 2.4), little or no data yet exists on which to base a judgement of what value  $P_2'$  should have, it is recommended that  $P_2'$  be assigned the value of zero for the present. Then, with  $P_2'$  fixed at zero, the following table may help in selecting a value for  $b_1$  to represent a given area.

<u>Past Experience In Area</u>	<u>Value of <math>b_1</math></u>
The accumulated effect of subgrade movements barely noticeable 12 to 15 years after construction	.02
The accumulated effect of subgrade movements noticeable 3 to 6 years after construction	.08
Severe heaving of subgrade noticeable within 1 year of construction	.32

The value  $b_1 = 0$  is excluded since it is inconceivable that no subgrade movements whatever will occur during the life of a pavement.



## CHAPTER 6 - COSTS USED IN THE COMPUTER PROGRAM

There are a number of cost considerations associated with the investment in a pavement. Other than initial construction, this investment is accumulated throughout the life of the structure in the form of different types of maintenance charges. At the end of the analysis period, the pavement will usually have some salvage value (although this may be a negative value). A complete list of these cost considerations may be outlined as follows:

- I. Initial construction cost
- II. Future costs
  - A. Overlay costs
    - 1. Overlay construction costs
    - 2. User costs due to traffic delays
  - B. Annual routine maintenance costs
  - C. Seal coat costs
- III. Salvage value

The purpose of this chapter is to describe how each of these costs is computed.

Since the majority of these costs will be accrued in the future, their present values must be obtained for determining the present value of the total cost of the pavement.

The present value of the total cost may be computed as

$$TC = IC + MC + OC + SC - SV$$

where TC = the present value of the total cost.

IC = the cost of initial construction.

MC = the sum of the present values of annual routine maintenance cost.

OC = the sum of the present values of overlay construction and user costs.

SC = the sum of the present values of seal coat costs.

SV = the present value of salvage value at the end of the analysis period.

A description of how each of these quantities is calculated will be given in following sections. The cost of each of the above quantities will be in terms of cost per square yard of pavement.

## 6.1 Cost of Initial Construction

The cost per compacted cubic yard in place for each material must be input into the computer program. The program will then determine the in-place cost per square yard per inch thickness by simply dividing by 36. The cost of initial construction can then be computed as

$$IC = \sum_{j=1}^n D_j C_j$$

where  $n$  = number of layers above the subgrade.

$D_j$  = depth of the  $j^{\text{th}}$  layer (inches).

$C_j$  = in-place cost/sq. yd./in. of the material used in the  $j^{\text{th}}$  layer.

## 6.2 Annual Routine Maintenance Costs

The cost of annual routine maintenance during each year after initial or overlay construction is assumed to increase at a uniform rate of the form

$$\text{ANNUAL COST} = C_1 + (m-1) C_2$$

where  $C_1$  = routine maintenance cost/sq. yd. during the first year after initial or overlay construction.

$m$  = number of years after initial or overlay construction.

$C_2$  = incremental increase in routine maintenance cost/sq. yd. per year.

The model that has been developed assumes that all costs occurring within a year are paid at the beginning of that year. After an overlay the cost of routine maintenance during the following year is again  $C_1$ . The present value of all routine maintenance charges during the analysis period can be found from

$$\text{RM} = \sum_{m=1}^{M_1} \frac{C_1 + (m-1) C_2}{(1+i)^{m-1}} + \sum_{m=1}^{M_2} \frac{C_1 + (m-1) C_2}{(1+i)^{L_2+m-1}} + \dots + \sum_{m=1}^{M_K} \frac{C_1 + (m-1) C_2}{(1+i)^{L_K+m-1}}$$

where RM = present value of the total cost per sq. yd. of all routine maintenance during the analysis period,

$i$  = interest rate.

$M_k$  = number of years in the  $k^{\text{th}}$  performance period =  $t_k - t_{k-1}$ , where  $t_k$  and  $t_{k-1}$  are rounded to the nearest integer before  $M_k$  is calculated.

$K$  = number of performance periods within the analysis period.

$$L_k = \sum_{j=1}^{k-1} M_j$$

The last performance period is truncated to terminate at the end of the analysis period so that maintenance costs beyond the analysis period are not considered.

### 6.3 Overlay Construction Cost

Calculation of the overlay construction cost amounts to no more than computing the present value of all future overlays. In general, it is assumed that overlays will be constructed from asphaltic concrete. It is also assumed that an overlay must be at least 1/2 inch thick, and that all overlays greater than 1/2 inch must be in even increments of a half inch.

The final assumption is that each time an overlay is constructed, there is an additional charge equal to the cost of one inch of overlay. This additional charge is included as a level-up cost.

The present value of the total cost attributed to overlay construction is

$$OC = \sum_{k=1}^{K-1} \frac{C_1 O_k + C_1}{(1+i)^{t_k}}$$

where  $K-1$  = number of overlays constructed in analysis period (there are  $K$  performance periods).

$C_1$  = cost/sq. yd/inch of asphaltic concrete.

$O_k$  = overlay thickness, not including the level-up inch, applied at the end of the  $k^{\text{th}}$  performance period.

$t_k$  = time (rounded to the nearest year) at the end of the  $k^{\text{th}}$  performance period, as previously defined.

#### 6.4 Seal Coat Costs

The model for the application of seal coats assumes that the design engineer will specify the cost per lane mile of applying a seal coat and a schedule of (1) the time in years before the first seal coat,  $\tau_1$ , and (2) the time in years between subsequent seal costs,  $\tau_2$ . These two times may be identical without loss of generality. This schedule is to initiate after initial construction and after each overlay.

It is assumed that a seal coat does not affect the serviceability index of the pavement. It is also assumed that a seal coat will not be applied within one year prior to an overlay.

The computer program first converts the seal coat cost to cost/sq. yard of pavement. The determination of the present value of all seal coats is actually rather simple to describe but rather complicated to formulate mathematically. The basic idea is that of taking the following sum

$$SC = \sum_{j=1}^{NUM} \frac{SCC}{(1+i)^{y_j}}$$

where SC = present value per sq. yard of all future seal coats,

SCC = cost/sq. yard of a seal coat,

i = interest rate,

NUM = total number of seal coats,

$y_j$  = year in which the  $j^{\text{th}}$  seal coat is applied.

To be more specific:

$$SC = \sum_{k=1}^K \sum_{j=1}^{J_k} \frac{SCC}{(1+i)^x}$$



where SC = present value per square yard of all future seal coats,

SCC = cost per sq. yard of a single seal coat,

i = interest rate,

K = number of performance periods (which is equal to one plus the number of overlays within the analysis period)

$x = \left[ t_{k-1} + \tau_1 + (j-1) \tau_2 \right]$ , where  $t_{k-1}$  is the number of years, after initial construction, that elapse before the beginning of the  $k^{\text{th}}$  performance period, with  $t_0=0$ , and  $\tau_1$  and  $\tau_2$  are as previously defined, and

$J_k$  = the number of seal coats in the  $k^{\text{th}}$  performance period,

and where:

$$J_k = \begin{cases} \frac{t_k - t_{k-1} - \tau_1 - 1}{\tau_2} + 1 & , \text{ if } t_k - t_{k-1} \geq \tau_1 + 1 \\ 0 & , \text{ otherwise.} \end{cases}$$

The reason the one is subtracted from the numerator of the first part of the above equation is because of the assumption that no seal coat is applied within one year prior to an overlay. The quantity  $J_k$  as calculated is rounded down, i.e., truncated, to integer form.

## 6.5 Traffic Cost of Overlay

The purpose of this section is to describe the procedure for calculating users' (or motorists') increase in costs due to overlaying operations. These costs include those associated with delay (time), vehicle operation, and accidents. Only delay and vehicle operating costs are considered at this time since there is little information on how accident rates are affected by overlaying. The purpose of the section is to give formulas for calculating these traffic costs and to indicate what inputs must be provided by the program user for a specific job. Although five methods of handling traffic are discussed, only the first method has been written in the computer program; the other four methods will be written in four subroutines which will be added to the computer program in the next year of the project. Also it is expected that the same general method will be used for evaluating the traffic cost associated with applying seal coats.

This section is divided into four sub-sections, the first of which describes the assumed speed profiles of vehicles in the vicinity of the overlay operation. The second sub-section gives the time and operating costs associated with the different movements described by the speed profiles. In the third sub-section the five methods of handling traffic are described and equations are given for calculating the proportion of vehicles stopped and the average time stopped for conditions where traffic congestion arises because of the overlay operation. The final sub-section gives formulas for calculating total user cost and total user cost per square yard of pavement.

### 6.5.1 Speed Profiles

It is assumed that all vehicles approach the overlay area at the same speed, called the "approach speed." It is further assumed that there is a "restricted area," the length of which is  $L_s$  (in miles), through which vehicles travel at a reduced speed. For some methods of handling traffic this reduced speed may be the same for vehicles traveling in both directions but for other methods it may be different for each direction; it is assumed to always be the same for all vehicles going in the same direction. Generally, the vehicles traveling in the "overlay direction" will have their speed reduced as much or more than will those traveling in the "non-overlay direction."

The length  $L_s$  of the restricted area generally will be longer than the length  $L_o$  of the actual overlay operation. The amount by which  $L_s$  is longer than  $L_o$  will be determined by the road geometrics and the method of handling traffic. This is discussed more fully below in the section on methods of handling traffic.

As was mentioned above it is assumed that vehicles approach the restricted area at an "approach speed" denoted by  $SA$ . If there were no overlay taking place then the vehicles would travel through the area which is restricted during overlay at the "approach speed." During overlay, however, most vehicles travel through the restricted area at a reduced speed called the "through speed, overlay direction" denoted by  $SO$  or the "through speed, non-overlay direction" denoted by  $SN$ . It is assumed that vehicles maintain these "through speeds" all the way through the restricted area.

A proportion (called  $PO_1$  in the overlay direction and  $PN_1$  in the non-overlay direction) of all vehicles will be stopped as they approach the restricted area. It is assumed that these vehicles stop and then accelerate back to the through speed which is reached at the moment they enter the restricted area of length  $L_s$ ; the vehicles then travel at the reduced speed (SO or SN) through the restricted area for a distance of  $L_s$  and as soon as they leave the restricted area they return to a speed which is the same as their approach speed.

Figure 11 shows the speed profile for such a vehicle which is stopped. The letters along the horizontal axis denote points where speeds are changed. The vehicle approaches the restricted area at a speed of SA, begins decelerating at point A and is stopped by the time it reaches point B, remains stopped for a time ( $DO_1$  in the overlay direction and  $DN_1$  in the non-overlay direction) at point B, then accelerates back to the through speed SO or SN which is reached at point C which is the beginning of the restricted area of length  $L_s$ , then travels from point C to point D at the through speed, and at point D begins accelerating back to the approach speed which is reached at point E.

Vehicles which do not stop are slowed down when they pass through the restricted area and it is assumed that their deceleration is such that they reach the through speed (SO or SN) at the moment they enter the restricted area. The proportion of vehicles which do not stop equals one minus  $PO_1$  for the overlay direction and one minus  $PN_1$  for the non-overlay direction.

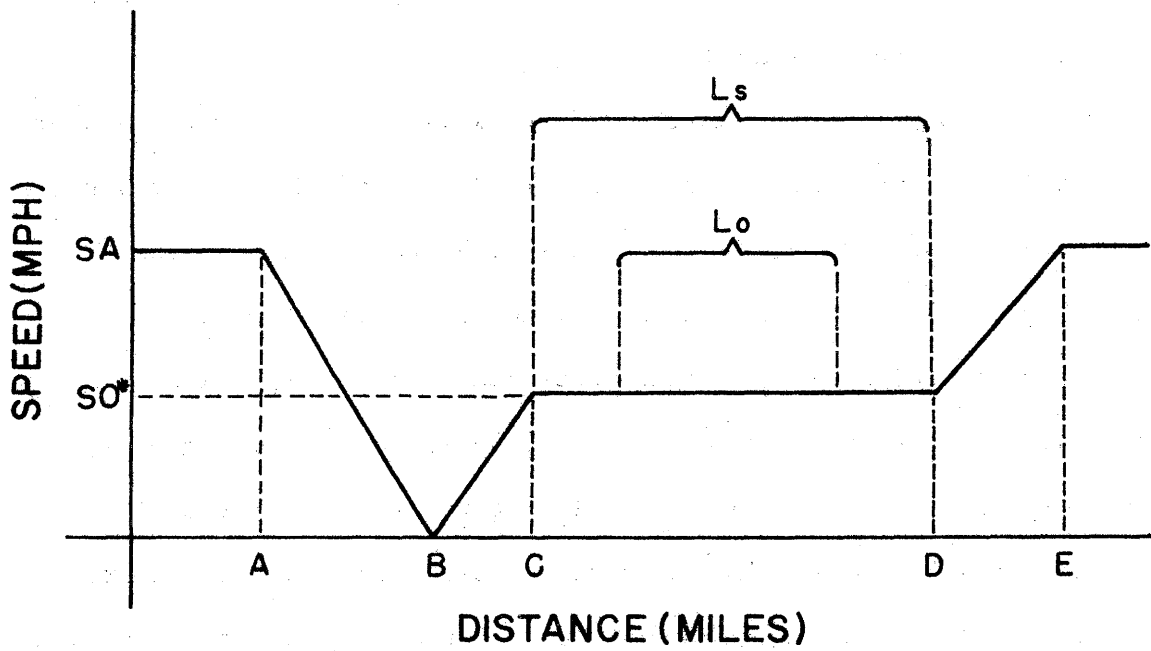


Figure 11: Speed profile for vehicles which are stopped during overlay.

\* This speed is  $S_0$  in the overlay direction but would be  $S_N$  in the non-overlay direction.  $L_o$  is length of overlay work;  $L_s$  is length of restricted area.

Figure 12 shows the speed profile for a vehicle which is not stopped but is slowed by the overlay operation. The letters along the horizontal axis denote points where speeds are changed. The vehicle approaches the restricted area at a speed of  $S_A$ , begins decelerating at point A, decelerates to the through speed  $S_0$  or  $S_N$  which is reached at point B which is the beginning of the restricted area of length  $L_s$ , continues at the through speed from point B to point C which is at the end of the restricted area, then at point C begins accelerating back to the approach speed which is reached at point D.

Because of overlay operations, vehicles will travel through the overlay area with speed profiles as shown in Figures 11 and 12. In the absence of overlay operations they would have traveled at the approach speed through the overlay area. The excess traffic costs due to overlay include the excess time and operating costs due to reducing from the approach speed to a stop (from A to B in Figure 11) and returning back to that speed (from B to C and from D to E in Figure 11), the excess time and operating (idling) costs due to being stopped (at point B in Figure 11), the excess time and operating costs due to reducing from the approach speed to the through speed (from A to B in Figure 12) and returning to the approach speed (from C to D in Figure 12), and the excess time and operating costs due to traveling a distance  $L_s$  (from C to D in Figure 11 and from B to C in Figure 12) at a reduced speed ( $S_0$  or  $S_N$ ) instead of traveling at the approach speed ( $S_A$ ). The excess costs of the aforementioned types are discussed in the next section.

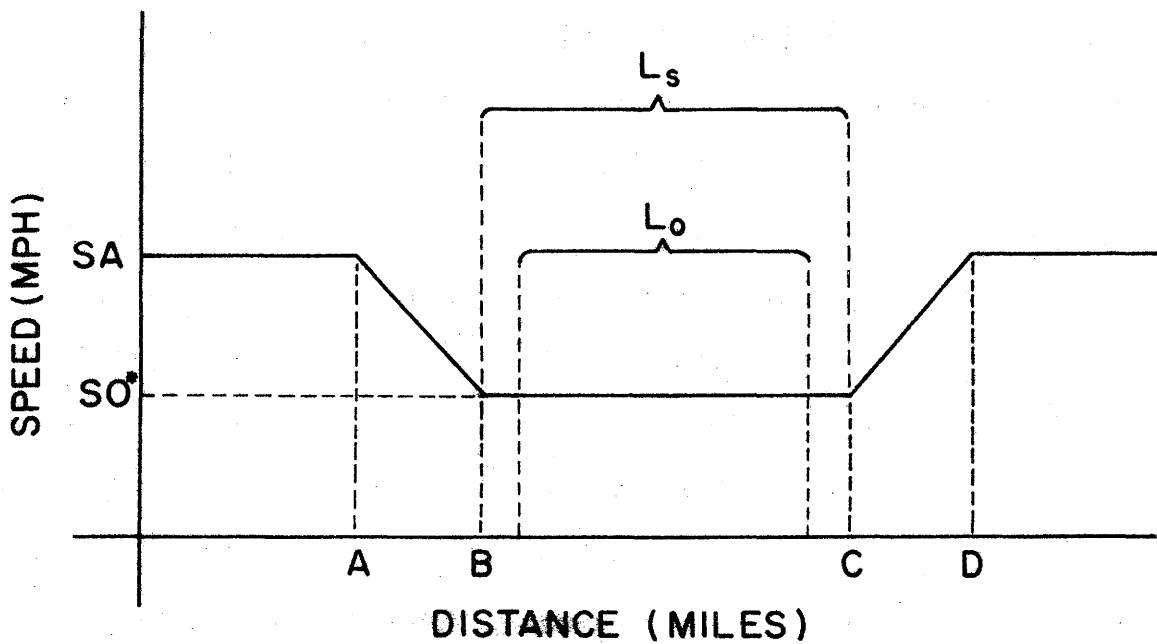


Figure 12: Speed profile for vehicles which are not stopped but are slowed during overlay.

\* This speed is  $S_0$  in the overlay direction but would be  $S_N$  in the non-overlay direction.  $L_o$  is length of overlay work;  $L_s$  is length of restricted area.

### 6.5.2 Time and Operating Costs

The excess user costs because of an overlay include the excess cost of stopping and slowing down, the cost of delay while stopped, and the excess cost of traveling at a reduced speed through the restricted area. The information needed for calculating these costs are given in Tables 6 through 9. The program user must stipulate whether the overlay operation is in an urban or rural area and this determines which tables or which columns in the table are used. The difference between the urban and rural costs is the vehicle distributions used to derive the costs. The operating costs for different types of vehicles were taken from a publication by Winfrey (5), and this same source was used for the excess time of making speed changes. The values of time used in calculations were based on information in studies by the Stanford Research Institute (6), Lisco (7), and Adkins (8). The proportions of vehicles of different types for urban and rural areas in Texas is taken from proportions for 1966 given in a study by the Planning Survey Division of the Texas Highway Department (9). The reason that the costs are higher for rural areas than for urban areas is that there is a higher proportion of trucks in rural areas and their costs are higher than those for passenger cars.

Tables 6 and 7 give the excess time and operating costs for stopping (in the first columns) and for slowing down (in the other columns). Table 8 gives the time and operating costs for operating at a uniform (constant) speed. Table 9 gives the time and operating costs of delay (or idling).



TABLE 6: DOLLARS OF EXCESS OPERATING AND TIME  
 COST OF SPEED CHANGE CYCLES - EXCESS COST ABOVE  
 CONTINUING AT INITIAL SPEED, FOR RURAL ROADS IN TEXAS

Initial Speed MPH	DOLLARS PER 1000 CYCLES, BY					
	SPEED REDUCED TO AND RETURNED FROM (MPH)					
	<u>0</u>	<u>10</u>	<u>20</u>	<u>30</u>	<u>40</u>	<u>50</u>
10	8.473					
20	18.200	9.413				
30	31.550	21.491	11.354			
40	50.360	39.609	28.422	15.795		
50	77.932	66.233	53.917	39.941	22.612	
60	120.546	106.979	92.482	76.022	56.405	32.485

TABLE 7: DOLLARS OF EXCESS OPERATING AND TIME  
 COST OF SPEED CHANGE CYCLES - EXCESS COST ABOVE  
 CONTINUING AT INITIAL SPEED, FOR URBAN ROADS IN TEXAS

Initial Speed MPH	DOLLARS PER 1000 CYCLES, BY SPEED REDUCED TO AND RETURNED FROM (MPH)					
	<u>0</u>	<u>10</u>	<u>20</u>	<u>30</u>	<u>40</u>	<u>50</u>
10	5.869					
20	11.769	5.602				
30	19.500	12.857	6.501			
40	30.030	22.933	15.976	8.607		
50	45.002	37.338	29.610	21.448	11.856	
60	67.868	58.992	49.114	40.242	29.360	16.432

TABLE 6: DOLLARS OF OPERATING AND TIME COST PER 1000  
VEHICLE MILES AT UNIFORM SPEEDS IN TEXAS

UNIFORM SPEED, MPH	DOLLARS PER 1000 MILES	
	RURAL ROADS	URBAN ROADS
5	\$750.20	\$692.06
10	393.47	362.43
15	274.15	252.21
20	214.53	197.06
25	179.13	164.16
30	156.05	142.57
35	140.18	127.58
40	129.03	116.84
45	121.06	108.98
50	115.51	103.24
55	111.94	99.18
60	110.16	96.73

TABLE 9: DOLLARS OF OPERATING AND TIME COST OF DELAY (OR IDLING) PER 1000 VEHICLE HOURS, FOR TEXAS

TYPE OF DELAY COST	DOLLARS PER 1000 HOURS	
	RURAL ROADS	URBAN ROADS
Operating	\$ 132.22	\$ 122.89
Time	3,367.54	3,140.22
Total	3,499.76	3,263.11

### 6.5.3 Methods of Handling Traffic

There are several methods of handling traffic during an overlay operation. The method used depends mainly on highway geometrics, especially the number of lanes, the type of median (if any), and the presence or absence of pavement shoulders, frontage roads, or other alternate routes. In the two following subsections are described the five methods of handling traffic which are most commonly used and the way of calculating average delay and proportion of vehicles stopped for each method.

The five methods. The first two methods of handling traffic are for two-lane roads (with or without shoulders) and the other three methods are for roads with four or more lanes. Figures 13 through 17 depict in a general way the five situations. In each figure  $L_o$  and  $L_s$  are shown.  $L_o$  is the amount of road which is overlaid at any one time - not the total overlay job length.  $L_s$  is the distance over which traffic is slowed down by the overlay operation at any one time. In the situations depicted in Figures 13, 14, and 15,  $L_s$  is only slightly longer than  $L_o$  by say one-tenth of a mile, but in the situations depicted in Figures 16 and 17,  $L_s$  may be considerably longer than  $L_o$ .  $L_s$  and  $L_o$  are job variables provided by the program user and should be "expected" average values. If  $L_o$  and  $L_s$  are not constant then the total overlay should be divided into several  $L_o$  and  $L_s$  sections and the traffic costs should be calculated separately for each; the program, nevertheless, assumes they are constant. In the figures, the "overlay direction" is always to the left (or westward).

Method I (see Figure 13). For two-lane roads with shoulders, one lane of traffic can be diverted onto a shoulder. Traffic going "west"

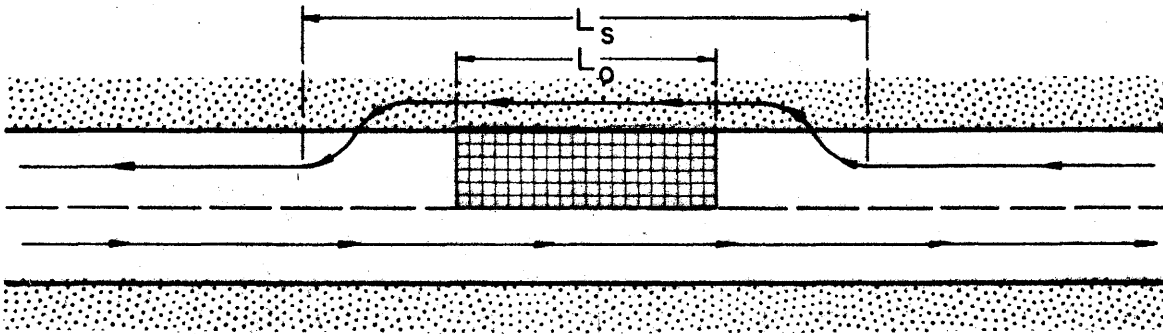


Figure 13: Method I. Traffic routed to shoulder.

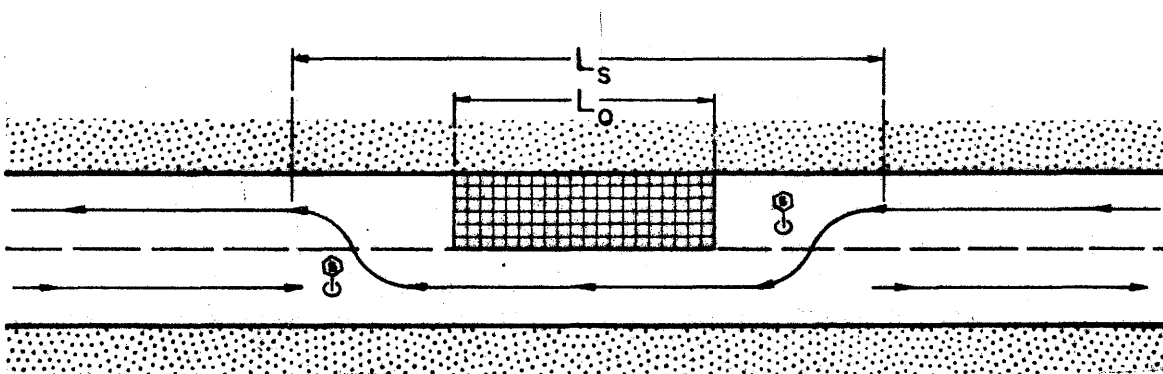


Figure 14: Method II. Alternating traffic in one lane.

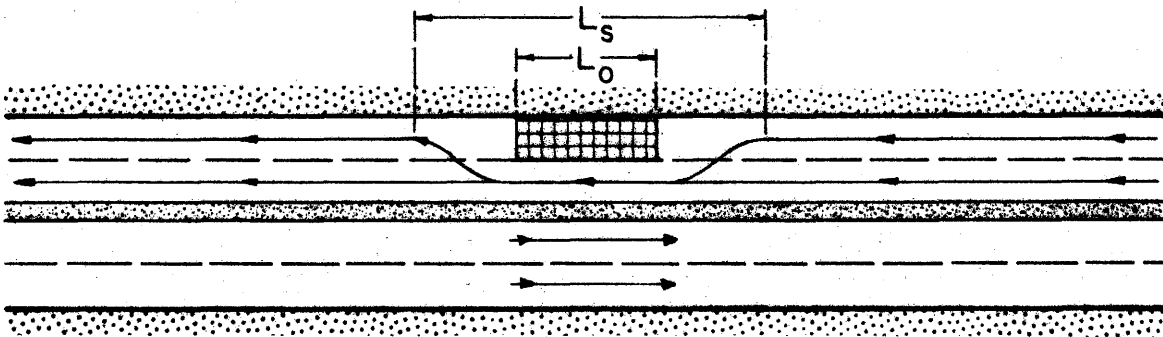


Figure 15: Method III. Two lanes merge, non-overlay direction not affected.

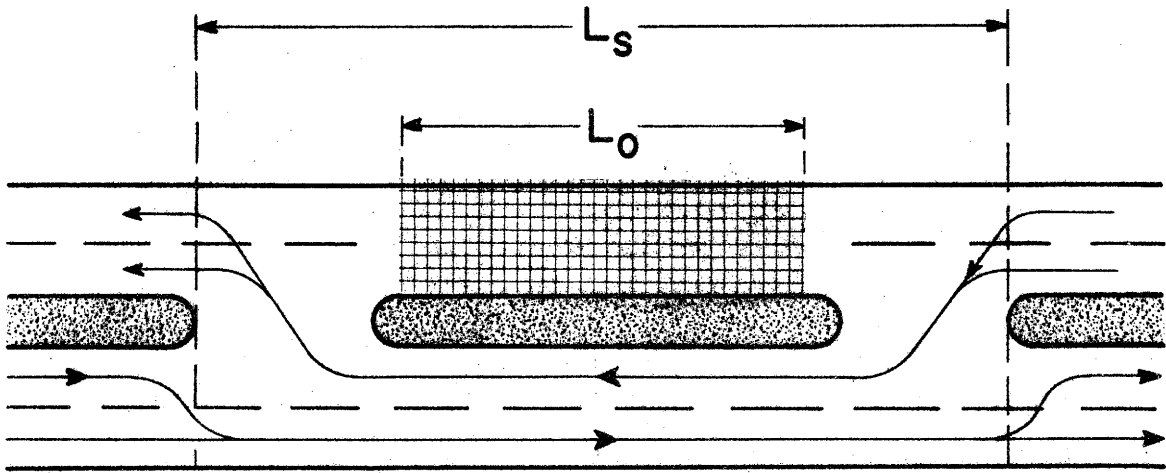


Figure 16: Method IV. Overlay direction traffic routed to non-overlay lanes.

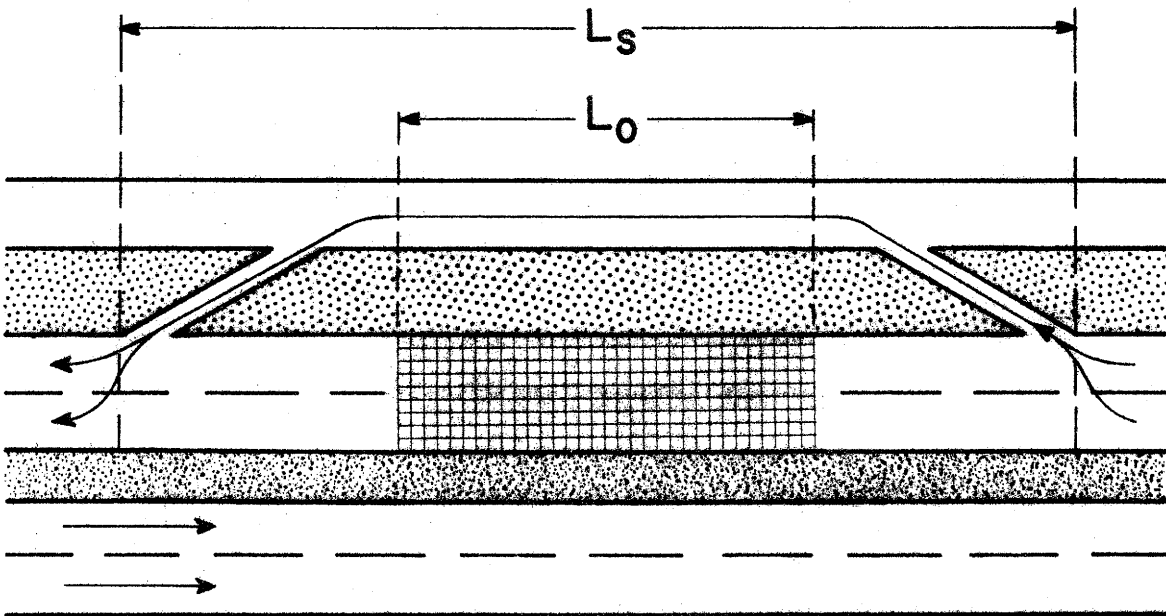


Figure 17: Method V. Overlay direction traffic routed to frontage road or other parallel route.

in the "overlay direction" can be diverted onto the shoulder as shown in Figure 13 and such traffic will generally be slowed down. Traffic in the non-overlay direction proceeds as usual but also must slow down though probably not by as much as the traffic going in the overlay direction. Another version of this method is to divert the traffic in the non-overlay direction onto their shoulder and divert the traffic going in the overlay direction into the eastward lane. In addition to the delay due to traveling at a reduced speed, traffic may be additionally delayed by having to stop due to movement of overlay personnel and equipment in the overlay area and by the inability to overtake other traffic in the overlay area.

Method II (See Figure 14). For two-lane roads without shoulders, it is sometimes necessary to post flagmen at each end of the overlay operation and to stop traffic in one direction while traffic from the other direction proceeds through the overlay area. The flagmen determine from which direction traffic is let through the overlay area at any one time. The vehicle arriving first usually has priority. If an additional vehicle arrives while other vehicles going in the same direction are proceeding through the overlay area then this additional vehicle usually may also proceed through the area, except that it will be stopped when the vehicles in the queue from the other direction are of a number or have been waiting a time which justifies priority for them. Traffic from each direction travels through the overlay area at a reduced speed. Some vehicles from each direction are stopped to give way to vehicles from the opposite direction, or because of the movement of overlay personnel and equipment in the overlay area, or because vehicles do not have the ability to overtake other vehicles in the overlay area. Generally



speaking, the proportion of traffic stopped to give way to vehicles from the opposite direction will be higher the longer is  $L_s$  and the larger is the traffic volume.

Method III (See Figure 15). For roads with two or more lanes in each direction and with a non-transversable median, it is assumed that traffic in only one direction will be affected by the overlay operation. It is also assumed that at least one lane in the overlay direction remains open for traffic. For low traffic volumes the effects on traffic in the overlay direction will be that of reduced speed through the area, stops due to movement of overlay personnel and equipment, and inability to overtake other vehicles as easily. For higher volumes for which the flow of traffic is above the capacity of the restricted roadway, a queue will result upstream of the overlay operation and will lead to vehicles being stopped due to congestion.

Method IV (See Figure 16). For roads with two or more lanes in each direction and with no medians or with medians which can be crossed at any point or which have median openings, it may sometimes be desirable to block all lanes in the overlay direction and divert the overlay-direction traffic to non-overlay-direction lanes. Figure 16 depicts the situation for a road with median openings; the difference between this situation and those with either no median, or situations for which it is intended that traffic will cross the median immediately in front and behind the overlay job, is that  $L_s$  in these latter two cases would bear approximately the same relation to  $L_o$  as is the relation in Figures 13, 14, and 15 instead of being the distance between median openings at each end of the overlay job as is depicted in Figure 16. For these

situations both lanes of traffic will be affected, and the method of calculating average delay and proportion of vehicles stopped is the same as that used for Method III, but in Method IV traffic going in both directions is affected.

Method V (See Figure 17). In some situations traffic in the overlay direction is diverted to an alternate route such as a frontage road or some other parallel road or street.

Average delay and Proportion of Vehicles Stopped. The delay to traffic due to overlay is of four basic types which are related to vehicles:

- (1) traveling at a reduced "uniform" speed in the restricted area,
- (2) not having the ability to overtake and pass other vehicles traveling in the same direction,
- (3) having to stop because of the movement of overlay personnel and equipment in the overlay area, and
- (4) having to stop because of congestion when the traffic demand exceeds the capacity of the restricted area.

The delay per vehicle due to traveling at a reduced speed equals the travel time at the reduced speed through the restricted area minus the travel time vehicles would have had through the restricted area had it not been restricted.

The delay due to vehicles not having the ability to overtake and pass other vehicles traveling in the same direction because of the overlay operation may result both in the restricted area and outside the restricted area. This delay when it occurs in the restricted area is included in the delay discussed in the preceding paragraph if accurate estimates of speeds through the restricted area are used. The delay due to the

inability to pass outside the restricted area because of the overlay is a more complicated calculation and is probably largest in the cases where the capacity of the restricted area is smaller than the demand (or input) for use of the area. In such cases wherein demand exceeds capacity there will be congestion and queueing of vehicles. These queues must disperse after leaving the restricted area and before such dispersion occurs there probably will be some inability to pass outside the restricted area. Such effects probably will be small in all cases except Method II with considerable queueing. If the length of the restricted area is fairly long and/or the traffic volumes are fairly large, then in Method II there will arise fairly long queues of vehicles. Such queues arise in one direction while vehicles are traveling through the restricted area from the other direction; then, when this queue is allowed to proceed through the restricted area it will emerge as a moving queue, sometimes of considerable length, and extra delay will result outside the restricted area until the queue disperses. The rate of dispersion of this moving queue will depend mainly upon the amount of traffic from the opposite direction, the road geometrics, and the type of vehicles in the queue. This moving queue will also impede passing by traffic from the opposite direction; however, there will be a considerable length of road in front of this queue in which there will be no (or very few) vehicles which will somewhat offset the effects of the moving queue on traffic in the opposite direction. Since the type of delay discussed in this paragraph probably is small in most cases and since it is difficult to calculate, it is ignored (i.e., assumed to be zero).

The third type of delay, that resulting from vehicles having to stop because of the movement of overlay personnel and equipment in the

overlay area, is calculated by multiplying the number of vehicles stopped by the excess delay of stopping. The program user must estimate (1)  $PO_2$  and  $PN_2$ , the proportion of vehicles stopped due to the movement of overlay personnel and equipment and (2)  $DO_2$  and  $DN_2$ , the average time that each vehicle stopped (because of such movement) remains stopped. It is expected that the overlay operation will be conducted in a way such that the number of vehicles stopped due to the movement of overlay personnel and equipment will be small. Therefore, in the absence of information on the number of such stops, the program user probably should estimate that number to be near or equal to zero.

The last type of delay (denoted by  $DO_1$  in the overlay direction and by  $DN_1$  in the non-overlay direction) results when a proportion of vehicles (denoted by  $PO_1$  in the overlay direction and  $PN_1$  in the non-overlay direction) have to stop because of congestion which results when traffic demand or input per hour ( $Q$ ) exceeds the hourly capacity or output ( $\emptyset$ ) of the restricted area.

When Method I of handling traffic is used, this type of delay should be almost nonexistent and is assumed to be zero; i.e.,  $DO_1 = DN_1 = 0$  and  $PO_1 = PN_1 = 0$  for Method I.

When Method II of handling traffic is used, it is assumed that the hourly traffic is evenly divided between directions. It is also assumed that vehicle arrivals from each direction are Poisson. The proportion of vehicles stopped due to congestion from each direction ( $PO_1$  or  $PN_1$ ) is estimated by the following equation:

$$PO_1 (=PN_1) = \frac{(1 - e^{-aQ})^2}{2}$$

where;

a = the time that it takes a vehicle to travel through the restricted area, in hours, and

Q = the number of vehicles arriving at the overlay area per hour in the overlay direction.

An equation for estimating the average delay per stopped vehicle ( $DO_1$  or  $DN_1$ ) for Method II is developed from equations formulated by Tanner (10) and given by:

$$DO_1 (=DN_1) = \frac{(1 + e^{2aQ}) (e^{aQ} - aQ - 1)}{2Q(e^{2aQ} - e^{aQ} + 1) PO_1}$$

where a, Q and  $PO_1$  are as previously defined.

When Method III or V is used, both  $PN_1$  and  $DN_1$  will equal zero. When Method III, IV, or V is used to handle traffic  $DO_1$  for all three methods and  $DN_1$  for Method IV are calculated using the following equation developed and verified by the California Division of Highways (11):

$$DO_1 = \frac{H(Q - \phi)(R - \phi)}{2Q PO_1 (R - Q)} \quad \text{if } Q > \phi$$

$$DO_1 = 0 \quad \text{if } Q \leq \phi$$

where;

H = the number of hours per day that overlay construction takes place,

R = the recovery rate in vehicles per hour,

$\phi$  = the restricted output rate in vehicles per hour,

and Q and  $PO_1$  are as previously defined.

It is assumed that the input rate Q is the same for both directions of travel and equals 6 percent of average daily traffic in rural areas and

5 percent of average daily traffic in urban areas. The output rate  $\phi$  and recovery rate  $R$  are taken from the California study (11) and are given in Table 10. The California study also gives the number of vehicles which will be stopped at the time when recovery begins, i.e., when all lanes are reopened for travel, and this number equals  $H(Q-\phi)$ . The average number of vehicles which will be stopped at any one time during overlay will be  $H(Q-\phi)/2$ . By assuming that each vehicle which is stopped stays stopped for some average amount of time  $D$ , which is assumed to equal 1/12 hour, not including the time stopped after recovery begins, and assuming that no vehicles are stopped after recovery begins, the total number of vehicles stopped can be estimated as  $H^2(Q-\phi)/2D$  if  $Q > \phi$  and is zero if  $Q \leq \phi$ . Thus, for Method III, IV, or V, the proportion of vehicles stopped  $PO_1$  (and also  $PN_1$  for Method IV) is estimated by dividing the total number of vehicles stopped by the total input of vehicles during overlay ( $H \times Q$ ):

$$PO_1 = \frac{H(Q - \phi)}{2DQ} \quad \text{if } Q > \phi$$

$$PO_1 = 0 \quad \text{if } Q \leq \phi,$$

with the constraint that: if this value exceeds 1.0, it is assigned a value of 1.0.

More research, including field observations, needs to be done on the precise number of stops under stop-and-go operation which results from congestion. Use of the above formulas gives reasonably accurate estimates of hours of delay but may underestimate the vehicle operating costs associated with stop-and-go operation.

TABLE 10 - CAPACITY TABLE

(Input rates greater than the output rates listed will normally result in the formation of a queue.)

Percent Trucks	No. of Lanes One Direction (Normal Operation)	2	3	4
	No. of Lanes One Direction (Restricted Operations)	1	2	3
0 - 10 (Urban)	Output Rate $\emptyset$	1400	2800	4500
	Recovery Rate R	3000	4700	6400
Over 10 (Rural)	Output Rate $\emptyset$	1350	2700	4350
	Recovery Rate R	3000	4500	6200

Note: The rates as listed above are veh/hr in one direction.

#### 6.5.4 User Cost Equations

The formula used for computing the total user cost TUC for an entire overlay operation is, prior to discounting to present value:

$$TUC = 2V \left[ PO_1(CO_1+CO_2+CO_3) + (1-PO_1)(CO_3+CO_4) + PO_2(CO_5) \right. \\ \left. + PN_1(CN_1+CN_2+CN_3) + (1-PN_1)(CN_3+CN_4) + PN_2(CN_5) \right]$$

where the variables with an "O" refer to the overlay direction and with an "N" refer to the non-overlay direction and where:

V is the number of vehicles affected by the overlay in either the overlay direction or the non-overlay direction which are equal because of the assumption of an equal directional split of traffic (See the formula for V below).

PO<sub>1</sub> and PN<sub>1</sub> are the proportions of traffic which are stopped due to the capacity of the restricted section being less than the demand for it, i.e., the proportions stopped because of congestion.

PO<sub>2</sub> and PN<sub>2</sub> are the proportions of traffic which are stopped due to the movement of overlay personnel and equipment in the restricted area.

CO<sub>1</sub> and CN<sub>1</sub> are the excess costs per vehicle of stopping from the approach speed and are the values given in the first columns of Tables 6 and 7, divided by 1000. CO<sub>1</sub> = CN<sub>1</sub> in all cases.

CO<sub>2</sub> and CN<sub>2</sub> are the costs per vehicle of idle time for vehicles stopped and are derived by multiplying DO<sub>1</sub> and DN<sub>1</sub> by total idling cost from Table 9, divided by 1000.

CO<sub>3</sub> and CN<sub>3</sub> are the excess costs per vehicle of traveling through the restricted area of length L<sub>s</sub> at a reduced speed and are equal to L<sub>s</sub> multiplied by the difference between the cost of operating at the reduced speed SO (or SN) and the cost of operating at the



approach speed SA, both taken from Table 8 and divided by 1000.  $CO_4$  and  $CN_4$  are the excess costs per vehicle of slowing from the approach speed SA to through speed SO or SN and returning to the approach speed and these costs are costs taken from Tables 6 and 7 divided by 1000.

$CO_5$  and  $CN_5$  are the excess costs per vehicle of stopping from the through speed SO or SN taken from Tables 6 and 7, and divided by 1000, plus the cost of idling while stopped due to the movement of overlay personnel and equipment which is obtained by multiplying  $DO_2$  and  $DN_2$  by appropriate values from Table 9 and dividing by 1000.

The computer program determines, from values given in Tables 6 through 9 and from inputs provided by the program user, values for costs  $CO_1$ ,  $CO_2$ ,  $CO_3$ ,  $CO_4$ ,  $CO_5$ ,  $CN_1$ ,  $CN_2$ ,  $CN_3$ ,  $CN_4$ , and  $CN_5$  and also  $PO_1$  and  $PN_1$ . The program user must provide  $PO_2$  and  $PN_2$  in the above equation but must also provide certain inputs (SA, SO, SN,  $DO_2$  and  $DN_2$ ) for calculating the costs and for calculating V as is described below. SA is the speed at which vehicles approach the overlay area, SO is the reduced speed at which vehicles pass through the restricted area in the overlay direction, SN is the reduced speed at which vehicles pass through the restricted area in the non-overlay direction,  $DO_2$  is the average length of delay for vehicles which are stopped in the restricted area because of the movement of overlay personnel and equipment, and  $DN_2$  is analogous to  $DO_2$  but for the non-overlay direction.

The number of vehicles affected by the overlay operation in one direction is calculated using this equation:

$$V = N_L \frac{L_T}{L_O} T P(PS) Hr_t$$

where

$N_L$  is the total number of traffic lanes to be overlaid in one direction,

$L_T$  is the total length of the road to be overlaid, in miles.

$L_O$  is the length of road being overlaid at any one time, in miles.

$T$  is the length of time, in days (or proportion of a day), that it

takes to make one overlay pass of two or less inches thickness of length  $L_O$ .

$P$  is the proportion of average daily traffic,  $r_t$ , that will pass through the overlay area during each hour of the day that overlay takes place and is assumed to be .06 for rural areas and .055 for urban areas.

$PS$  is the number of overlay passes made and is calculated in the computer program.

$H$  is the number of hours per day that overlay construction takes place (and probably is between 6 and 12 hours).

$r_t$  is the average daily traffic at time  $t$ , where  $t$  is the time of overlay as computed internally by the computer program, and is calculated within the program from inputs  $r_o$ ,  $r_c$ , and  $C$  which are provided by the program user as inputs for the "traffic equation" described in a previous chapter.

The program user must provide  $N_L$ ,  $L_T$ ,  $L_O$ ,  $T$ , and  $H$ .  $P$  is an assumed value.  $PS$  is calculated internally in the computer program.  $r_t$  is also

calculated internally by the computer program from  $r_o$ ,  $r_c$ , and  $C$  (which are provided by the program user as discussed in a previous chapter) and  $t$  which is calculated in the program and depends on several variables previously discussed. The equation for  $r_t$  is linear with respect to time, the assumption being that average one-way daily traffic is initially  $r_o$  and increases linearly to  $r_c$  at the end of the analysis period which is  $C$  years long:

$$r_t = r_o + \frac{t(r_c - r_o)}{C}$$

The total user cost per square yard TUCSY is calculated by dividing total user cost TUC by the total square yards TSY where TUC is as previously defined and TSY is given by:

$$TSY = 2N_L L_T L_W \frac{(5280)}{9}$$

where  $N_L$  and  $L_T$  are as previously defined and  $L_W$  is the width of one traffic lane, in feet.

## 6.6 Analysis Period and Salvage Value

The analysis period is the period of time over which costs are computed. Ideally the analysis period should end when the road is expected to be abandoned or when it is expected that major reconstruction work will be done on the road. It is possible to have an analysis period longer or shorter than this but since a longer period brings several complications into the analysis it should be avoided.

In practice, it is best to use an analysis period such that the program inputs can be reasonably estimated during that period. The period probably should be at least 15 years but usually not more than 30 years.

The salvage value of a pavement at the time it is abandoned or has major reconstruction work done on it is the value of the useable materials in the pavement less the cost of making them useable or disposing of them. If major changes in vertical and horizontal alignment are made at the time of reconstruction, then the salvage value probably will be less than it would have been otherwise. The salvage value will be negative if materials must be removed and their value in their new use is less than the cost of their removal; it is expected, however, that this usually will not be the case for asphaltic pavements.

Although most previous pavement comparisons have used very low salvage values even for relatively short analysis periods, there seems to be little justification for this. The salvage value at the end of short

analysis periods such as 15 or 20 years probably exceeds 50 percent much of the time. Since the salvage value depends on circumstances which are different for different roads, it is left to the program user to stipulate the percent that salvage value is of the cost of initial construction and overlay construction. Salvage values per square yard, SV, is then calculated using the following equation:

$$SV = \frac{P_{sv}}{100} \left[ \frac{\sum_{j=1}^n D_j C_j + \sum_{k=1}^{K-1} C_1 O_k}{(1+i)^C} \right]$$

where:

- $P_{sv}$  = the percent that salvage value is of the cost of initial construction and overlay construction.
- $D_j$  = the depth of the jth layer of material in the initial construction.
- $C_j$  = the cost per square yard/inch of the material in the jth layer.
- $C_1$  = the cost per square yard/inch of overlay construction.
- $O_k$  = the depth in inches of the kth overlay.
- $n$  = the number of layers of pavement in the initial construction.
- $K$  = the number of performance periods (and K-1 is the number of overlays).
- $C$  = the length of the analysis period.

## 6.7 Interest Rate

In the computer program, pavement designs are compared on the basis of the present value of total costs. Future costs and salvage value are discounted to the present to obtain their present value. A review of interest rates reveals that most interest rates which are used or are recommended for use are from 3 to 7 percent. Although some people have used a zero interest rate in pavement comparisons, their usage of this zero rate usually was based on the fact that they "did not borrow the money so no interest should be charged." Whether money is borrowed should have no effect on using an interest rate. The use of an interest rate is to show that funds used for pavement have alternative uses and the interest rate should give an indication of the rate of return in these alternative uses.

The program user must specify an interest rate.

## CHAPTER 7 - INPUT/OUTPUT OF THE COMPUTER PROGRAM

A list of the computer program's inputs and outputs discussed previously is given below.

### 7.1 Inputs to Computer Program

1. Number of construction materials available.
2. Funds (per sq. yd.) available for initial construction.
3. Length of analysis period in years (C).
4. Interest rate (i).
5. Lane width in feet ( $L_w$ ).
6. Performance variables:
  - a. District temperature constant ( $\alpha$ ).
  - b. Maximum serviceability index ( $P_1$ )
  - c. Minimum serviceability index ( $P_2$ ).
  - d. No-traffic lower bound on serviceability index ( $P_2'$ ).
  - e. Swelling clay rate parameter for first performance period ( $b_1$ ).
7. Traffic variables (one direction)
  - a. Initial ADT ( $r_o$ ).
  - b. ADT at the end of analysis period ( $r_c$ ).
  - c. Number of 18-kip axle applications accumulated in C years ( $N_c$ ).
8. Minimum time considerations (years)
  - a. Minimum time to first overlay. ( $t_1$ )
  - b. Minimum time between overlays.
  - c. Time to first seal coat after initial or overlay construction.
  - d. Time between seal coats.
9. User cost variables
  - a. Number of lanes in each direction ( $N_L$ ).
  - b. Total length of project (miles) ( $L_T$ ).

- c. Average length of overlay strip (one lane) ( $L_o$ ).
  - d. Average time to overlay this strip with 2" or less (days) (T).
  - e. Proportion of ADT passing through overlay zone during each hour that overlay construction takes place (P).
  - f. Hours/day that overlay construction takes place (H).
  - g. Class of highway (rural or urban).
  - h. Proportion of average daily traffic stopped in the overlay direction because of movement of overlay personnel and equipment in the overlay area ( $PO_2$ ).
  - i. Average delay per vehicle stopped in the overlay direction because of movement of overlay personnel and equipment in the overlay area ( $DO_2$ ).
  - j. Proportion of average daily traffic stopped in the non-overlay direction because of movement of overlay personnel and equipment in the overlay area ( $PN_2$ ).
  - k. Average delay per vehicle stopped in the non-overlay direction because of movement of overlay personnel and equipment in the overlay area ( $DN_2$ ).
  - l. Average traffic approach speed (mph) (SA).
  - m. Average speed through restricted area in overlay direction (mph) (SO).
  - n. Average speed through restricted area in non-overlay direction (mph) (SN)
  - o. Average length of restricted area (miles) ( $L_s$ ).
  - p. Type of traffic model (1,2,3,4, or 5).
10. Routine maintenance cost (per lane mile)
- a. Routine maintenance cost during first year after initial or overlay construction.
  - b. Annual incremental increase in routine maintenance cost.
11. Cost of seal coat (per lane mile)



12. User cost variables taken from Tables 6 through 10
  - a. Cost of changing speed/1000 cycles.
  - b. Cost of driving at reduced speed/1000 vehicle miles.
  - c. Cost of delay/1000 vehicle hours.
  - d. Output and recovery rates.
13. For each material above natural subgrade
  - a. Name of material.
  - b. Strength coefficient.
  - c. Cost per compacted cubic yard in place.
  - d. Minimum thickness allowed in initial construction (inches).
  - e. Maximum thickness allowed in initial construction (inches).
14. Strength coefficient of natural subgrade.
15. Percentage that salvage value of value of structure existing at end of analysis period.
16. Total thickness allowed in initial construction (inches).

## 7.2 Outputs of Computer Program

1. For each possible combination of materials -

A. Design with least overall cost

a. Materials used.

b. Initial construction thickness of each material (inches).

c. Life of initial construction (years).

d. Overlay schedule

(1) overlay thicknesses

(2) overlay times (years)

e. Seal coat schedule (years).

f. Initial construction cost.

g. Total routine maintenance cost.

h. Total overlay construction cost.

i. Total user cost.

j. Total seal coat cost.

k. Salvage value.

l. Total overall cost.

B. Next cheapest design

(Same information as above)

2. Summary of designs in order of increasing overall cost.

## CHAPTER 8 - THE OPTIMIZATION MODEL

Now that the principal physical equations and a number of cost relationships have been developed, the analysis is carried one step further. These equations and costs have been used as a basis for the development of a model for the optimization of flexible pavement design. Briefly, the objective of this model is to use available data and parameters to select the initial and overlay construction policies which result in minimum cost over an analysis period. This selection, however, is bounded by many restrictions, such as the minimum allowable time to the first overlay, the minimum allowable thickness of a material in initial construction, etc., as may be seen by reference to the program inputs listed in Chapter 7. It is these restrictions that force the model to yield solutions that are physically realistic. At the same time every attempt has been made to make the model as flexible and as general as possible.

This section of the report contains a brief description of the model. A computer program has been written which utilizes these concepts. This program is written in the FORTRAN IV language for the IBM 360/65 digital computer and has been forwarded to the Texas Highway Department under separate cover. Since the model is still conceptually new, an attempt has been made to design the optimization technique into modules so that sections may be revised with minimum effort as the need arises.

The optimization plan to determine the most economical design requires several steps. Each of these steps will be discussed. It should be emphasized at the outset that the intent of the discussion is not to show how the optimization is mathematically carried out but rather to give an understanding of the logical development of the model. In this sense, a verbal description of how the optimization works will be given rather than the actual development of the model.

Consider that some number of dollars are available for the entire cost of the project (this number is not actually known; it is only used for explanation). This would include the cost of the initial construction as well as all future costs. This available amount may be split up in many ways between these two considerations. A very weak pavement might be initially constructed in which case the future costs of maintaining the pavement would be rather expensive. On the other hand, a strong initial design would require very little in the way of future cost.

For this reason the overall optimization plan has been divided into these two stages: (1) optimization with respect to initial design and (2) optimization with respect to the overlay policy. It can be seen, however, that these two optimization problems are interrelated since the optimal overlay policy is dependent upon the initial design.

## 8.1 Initial Construction

It is assumed that a number of materials are available for initial construction. Each material has an associated strength coefficient along with a cost per compacted cubic yard, and restrictions on thickness in the initial construction. Thus, there are a number of combinations of materials that may be used for initial construction. The design with one layer above the subgrade would naturally consist of asphaltic concrete. Designs of two layers above the subgrade could also be enumerated by combining asphaltic concrete with each of the other materials. Other multiple layer designs can also be enumerated in the same manner.

The remainder of the optimization plan that follows must be carried out for each of these combinations of materials. As a result, the final solutions will be in the form of a set of optimal designs - one for each combination of materials.

Attention will next be turned to the actual optimization model for initial design. This model utilizes a branch and bound algorithm as the tool of optimization. This fact in itself is important from a theoretical point of view but is not of particular importance from the standpoint of being able to use the computer program. In other words, it is important to discuss what the technique does but not how it is done.

The important key to determining the optimal initial design is the deflection equation (1) which relates the design parameters and layer thicknesses to the surface curvature index of the pavement. This equation along with the available data for the in-place cost/sq. yd. inch of thickness for each material are all that is required to do this optimization.

Since each type of material has a lower limit on the thickness that will be constructed, there is a minimum design thickness for each combination of materials. The cost of this minimum design can easily be calculated by summing the products of each minimum depth times the in-place cost/sq. yd./inch of depth for each material used. The amount to be invested in initial construction will be allowed to vary in the increments of \$0.01 from the minimum on up to a prescribed maximum. For each of these amounts, the actual problem to be solved is that of determining the depths of each layer that will minimize the surface curvature index,  $S$ . Thus, the optimization process obtains the strongest design (in terms of  $S$ ) for each of the possible amounts that can be invested in initial construction. The deflection variable,  $S$ , for each of these designs can next be used in the performance equation (3) to determine the number of equivalent 18-kip single axles,  $N_1$ , that the pavement is expected to withstand before the serviceability index is reduced to its lower limit,  $P_2$ . From the traffic equation (2), which relates traffic to time, the length of time (in years) can be computed for each of these designs. This is the time,  $t_1$ , at which the first overlay is required (unless, of course, this time is longer than the analysis period,  $C$ ). This completes the first stage of the optimization.

## 8.2 Overlay Optimization

The second stage of the optimization is one of determining the optimal overlay policy for each design. Here, again, there are a number of possible alternatives. A thick overlay might carry the pavement through the remainder of the entire analysis period. It would, however, generally be more economical to construct a thin overlay on the pavement and plan another overlay later in the analysis period. This latter policy would have the advantage of deferring the second overlay cost so that the present value of this cost would be reduced. This policy would have the disadvantage, however, of increasing the user cost because of the traffic increase at that later time. Other possibilities are also available. In fact, all of the overlay possibilities can be graphically represented as a tree. Each branch of the tree would represent an individual overlay policy. Determination of the optimal overlay policy forms the second optimization problem. Even though sophisticated optimization techniques are possible, the problem has not been formulated as such because experience has shown that the actual number of branches in the tree is relatively small. It is faster and easier to actually enumerate the possible overlay policies. For example, assume that it is found that  $t_1$  years after the initial construction of a certain pavement, the serviceability index is down to  $P_2$ . There are several overlay possibilities available. A one inch overlay might last until time  $t_2$  in which case an additional overlay of one inch at that time might carry the pavement through the remainder of the analysis period. It, however, might be found that a two inch overlay laid at time  $t_1$  will also carry the pavement through the analysis period. The answer as to which of these alternatives is

most economical depends on the overlay cost as well as other cost factors.

The determination of the user cost, annual routine maintenance cost, overlay construction cost, seal coat cost, and salvage value have been discussed in Chapter 6. The present worth of each of these costs must be added (salvage value is treated as a negative cost) to obtain the total cost associated with each overlay policy. The most economical policy can then be selected. This cost is added to the cost of the initial design to determine the overall cost associated with that design. These overall costs are then scanned to determine (1) the design with minimum cost, and (2) the next cheapest design as an alternative. These two designs are determined for each combination of materials.



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## APPENDIX 1 - INPUT DATA REQUIREMENTS

The purpose of this section is to provide the program user with all the necessary instructions to properly input the required data. This is accomplished by providing graphical illustrations of the various input data card fields and the type of information they are to contain.

The required data for an example has been used to illustrate the use of these cards. Forwarded under separate cover is a complete listing of the computer program along with the output for the example problem. Comment cards inserted in the computer listing will also aid the programmer in the use of this program.

It is felt that the first 7 data cards need no additional explanation. The next three sets of data, however, might be difficult to interpret. These sets describe the excess operating and time costs of

1. reducing to and returning from a reduced speed in a rural area
2. reducing to and returning from a reduced speed in an urban area
3. driving at a uniform reduced speed

Each set contains 6 data cards. First consider the first two sets. The first card in each set assumes that the approach speed is 10 MPH, the second assumes an approach speed of 20 MPH, etc. The third set of data is similar; the first card assumes at reduced speed of 10 MPH, the second a reduced speed of 20 MPH, etc.

Finally the last set of data is for the available construction materials (one card for each). In attempting to combine these materials into the possible initial designs there is only one restriction. This is that the order in which the cards are input determines the arrangements in which these materials will be used. For example, if the card for lime

treated gravel is placed above the card for crushed gravel, their order will be preserved. That is to say that in all combinations involving these two materials, lime treated gravel will always be above crushed gravel, never below. This may be somewhat restrictive but it is felt that this is the best way to restrict the combinations to a logical sequence of materials (it would be undesirable to have asphaltic concrete as a subbase material). In any event, it is probably most logical to input the materials in the order of decreasing strength.







INPUT FORMAT COLUMN IDENTIFICATION																																																																															
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
										Minimum time between seal coats, TBSC										Format F10.1, --- 3.0																																																											
										Minimum time to the first seal coat, TTSC										Format F10.1, --- 5.0																																																											
										Minimum time between overlays, MTBO										Format I10, --- 5																																																											
										Minimum time to the first overlay, MTTO										Format I10, --- 5																																																											

Figure 21: Input format for minimum time variables





Data Card 6

INPUT FORMAT COLUMN IDENTIFICATION	0000000000 1234567891011121314151617181920212223242526272829303132333435363738394041424344454647484950515253545556575859606162636465666768697071727374757677787980	Type of model to be used for the traffic situation, <b>MODEL</b>	9999999999 1234567891011121314151617181920212223242526272829303132333435363738394041424344454647484950515253545556575859606162636465666768697071727374757677787980
		Format I10, _____ <u>1</u>	
		Length of overlay zone which affects traffic (distance in miles between barricades), <b>XLS</b>	
		Format F10.2, _____ <u>0 . 3 5</u>	
		Average speed through the overlay zone in the non-overlay direction, <b>ASN</b>	
		Format F10.1, _____ <u>4 0 . 0</u>	
		Average speed through the overlay zone in the overlay direction, <b>ASØ</b>	
		Format F10.1, _____ <u>3 0 . 0</u>	
		Average approach speed, <b>AAS</b>	
		Format F10.1, _____ <u>6 0 . 0</u>	
		Proportion of vehicles stopped in the non-overlay direction due to overlay construction, <b>PSN</b>	
		Format F10.0, _____ <u>5 . 0</u>	
		Proportion of vehicles stopped in the overlay direction due to overlay construction, <b>PSØ</b>	
		Format F10.1, _____ <u>1 0 . 0</u>	

Figure 23: Input format for the remainder of the user cost parameters













