A STUDY OF RELATIVE COSTS OF FLEXIBLE
HIGHWAY PAVEMENTS

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BY

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JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Final Report

A STUDY OF RELATIVE COSTS OF FLEXIBLE HIGHWAY PAVEMENTS

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

Project No.: 6-26-52H

File No.: 6-20-8

FROM: H. I. Michael, Associate Director
Joint Highway Research Project

December 3, 1970

The attached Final Report titled "A Study of Relative Costs of Flexible Highway Pavements" is submitted for acceptance as fulfilling the objectives of the Plan of Study of the same title approved by the Advisory Board on June 17, 1969. The research was performed and the report authored by Miss Farideh Samjerd, Graduate Assistant in Research on our staff. Professor E. J. Yoder directed the research and guided the preparation of the report.

The report presents a method for predicting the optimum initial service life and optimum periods of resurfacing for flexible pavements based on minimizing total pavement costs.

The report is presented to the Board for acceptance.

Respectfully submitted,

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Final Report

A STUDY OF RELATIVE COSTS OF FLEXIBLE HIGHWAY PAVEMENTS

by

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December 3, 1970

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ABSTRACT

Ramjerdi, Farideh, M.S., Purdue University, January 1971, A Study of Relative Costs of Flexible Highway Pavements. Major Professor: E. J. Yoder.

This thesis presents a method for predicting the optimum initial service life and optimum periods of resurfacing for flexible pavements. The method is based on consideration of total pavement costs including the cost of initial construction, routine maintenance and major maintenance and increased road user costs resulting from the maintenance operations.

Standard economic analyses techniques were used for determining the average annual cost of alternate designs. The model developed by Radzikowski for estimating routine maintenance cost of flexible highway pavements was modified and used in the analysis. The pavement design method developed by the Corps of Engineers was utilized in estimating initial design as well as required major maintenance (resurfacing). A method was developed which presented an estimation of road user cost due to maintenance and resurfacing operations.

Variables evaluated in this research included (1) subgrade type, (2) initial traffic volume, (3) rate of traffic growth, and (4) rate of interest on the investment. Solutions are presented for both 2-lane and 4-lane divided highways.

The results of the study are presented in the form of graphs which indicate the initial design period which results in least cost for all combinations of the variables given above.

INTRODUCTION

The function of a highway pavement is to provide a riding surface that adequately serves the demands of the road user with an acceptable level of performance. A great amount of research has been conducted into principles for the structural design of highway pavements. Many methods, based on an estimation of the strength of the pavement components coupled with an estimation of the amount of traffic which will use the pavement, are available to the engineer which enables him to determine the thickness requirements for flexible pavements.

Thickness requirements for flexible pavements are dictated in part by the accumulated effect of traffic that will use the pavement structure during its life. Design principles set forth in the AASHO Interim Guide, for example, are based upon an estimation of the total equivalent 18,000 pound single axle loads which will use the pavement during its service life. In general, a finite service life is assumed and then resurfacing of the pavement is planned for the end of the analysis period. Economics of the design generally dictate that the service life for a road which will carry a high volume of traffic should be greater than the service life for a road which will carry less traffic.

The ultimate aim of the highway engineer responsible for the planning and design of pavements is to provide a pavement which will maintain specified serviceability throughout the pavement's life, and

to provide the highway user with the best possible service at the lowest cost. There are two primary elements of cost which must be considered, (1) the average annual cost of the highway facility, including both initial and maintenance costs and (2) the average annual cost of operating motor vehicles on the pavement structure.

During the past ten to twenty years, extensive studies have been carried out for the purpose of development of mathematical models for predicting the routine maintenance cost of pavements. Usually variables such as traffic load, type of subgrade soil, environmental condition, and thickness of different layers of pavement have been found to be significant factors in these models.

Very little research has been conducted into methods of estimating costs resulting from accidents associated with maintenance operations. In cases where there have been need for considering these costs it has been the practice to assume a percentage of the total maintenance cost. These, however, are rough estimates at best.

A major decision that the design engineer must take is that regarding service life, and intervals at which major maintenance should be planned. Conceivably, for county roads and other low traffic highways, the most economic approach would be to plan for major maintenance at frequent intervals whereas for high traffic roads inconvenience to the road user generally dictates that service life should be done at greater intervals. There are little factual data in the literature which can provide the design engineer with a method for making decisions relative to the initial service life, and the optimum interval that should be considered for major maintenance.

BACKGROUND AND REVIEW OF LITERATURE

Road life studies are concerned with finding the life expectancy of the various elements that make up a highway. It is essentially a fiscal tool designed to determine the amount and cost of replacements required each year in the future on the determination of the life of roadway elements.

Many studies have been made to determine the useful lives of the various elements of a highway. There are many variables that needs to be considered including: soil, climate, topography, and traffic volume, each of these has an effect on the life of a type of pavement. Data have been compiled by various investigators which correlate surface type with average service life, average age, retirement rates, construction costs, and structural deterioration. (11)*

In general there are three types of probable lives to consider: First, the actual physical life, which is ended because of physical deterioration of the materials making up the pavement; second, the service life which is the length of the time that the facility is used in carrying out its original function without major rebuildings. Service life is ended when the facility is abandoned or rebuilt; third, the economic life, is determined by the time when the service rendered by that facility can be produced at a lower cost by a new facility. End of the economic life might result from rebuilding the old road, substitution of a different service, or by abandonment. Obviously economic life may not necessarily be the same length of time as

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

physical life or service life. All of these probable lives depend on traffic, subsoil conditions, environmental conditions, routine maintenance and the structural qualities of the pavement.

A report on the service lives of highways published by U. S. Bureau of Public Roads in 1956 presented data which showed that 82% of both flexible and rigid pavements reached the end of their service lives by reason of resurfacing and reconstruction (8). This indicates that resurfacing and reconstruction is a matter that should be planned for in advance.

J. W. Work (21) developed a mathematical model for predicting when pavement should be resurfaced. The service life dictated by this replacement model was based primarily on economics rather than engineering considerations. He proposed that replacement should be done when average cost is equal to marginal cost and marginal benefit.

E. P. Ulbricht (18) comparing alternate pavement designs, assumed that the service life of a surface is ended when its present serviceability reaches a minimum acceptable value.

In planning any transportation facility, not only the cost of the proposed facility but also the cost of various alternates must be considered. Normally, costs are separated into three categories (1) capital investments, including planning, design, and construction cost, (2) vehicle cost, including both operation and maintenance cost of the vehicle, and (3) cost of maintaining the facility. The important characteristic of these costs is that they are highly interrelated. Any change in design affecting construction costs also directly affects future maintenance and operating cost. Thus, the decision should be

based on probable overall cost rather than initial cost alone.

To compare alternate designs, the average annual costs of the alternates generally are compared. Methods for the determination of annual highway cost have been the subject of studies by several investigators and various methods have been developed for obtaining the average annual cost of a highway.

Major factors that affect the analysis of average annual cost are: initial construction costs, resurfacing costs, routine maintenance costs, salvage value, interest rate, and analysis period. Road user costs due to delay and accident during maintenance and resurfacing operations have been considered in some studies (10, 15). These items are described below to the extent that are related to the purpose of this study.

Initial Construction Cost

Initial construction cost can be computed on the basis of the thickness and composition of the designed pavement section and the unit price for each item of pavement including cost of the pavement surface, base, and subbase. This cost depends on variables such as service life, subsoil conditions, traffic to be handled during the service life of the pavement, environmental conditions, as well as the cost of material and labor.

Resurfacing Cost

This cost item can be computed on the basis of the thickness of resurfacing required at each stage and its unit price. Variables such as: resurfacing period, traffic to be handled prior to resurfacing, subsoil conditions, environmental conditions, rate of interest, will affect the resurfacing cost.

Routine Maintenance Cost

Highway maintenance can be defined as follows (20). "The preserving and keeping of each roadway, structure, and facility as nearly as possible in its original condition as constructed or as subsequently improved and such additional work as is necessary to keep traffic moving safely." Maintenance is a continuous operation, starting soon after initial construction is completed. An analysis of highway maintenance expenditures based on data gathered from wide geographical areas have shown great variation. A total of 34 different items have been identified that might influence maintenance cost (12).

To date, many studies have been conducted to develop models for predicting maintenance cost. In all these studies historical data have been used and, therefore, all predictions merely indicate what maintenance did cost, not what maintenance actually will cost. Usually variables such as: subsoil condition, traffic volume, thickness of different layers of pavement, pavement width, right-of-way widths, and environmental condition were found to be significant variables (2, 4, 14).

Maintenance expenditure and subdivided into different categories of which surface maintenance expenditures is of interest in this study.

Salvage Value

Oglesby has suggested a zero salvage value to be considered in economical studies of highways (11) whereas Winfrey (20) has suggested that the salvage value should be assumed to be low, especially for a pavement that will be difficult to be used in the future.

In the formula recommended by Baldock (3) for determining the annual costs to compare different alternative a salvage value is applied only to the last resurfacing.

Rate of Interest

A suitable rate of interest is a measure of the likelihood that the proposed alternative will be used for a number of years and will produce benefits estimated to prevail for the period of years used in the analysis.

Analysis Period

Winfrey (20) defines analysis period as follows: "A period of time usually much less than the estimated probable life of the property, which is chosen for purpose of economic analysis. Physically, highway property may have 50 to 100 years service life expected, but an analysis of the economic wisdom of constructing a highway facility based upon such extended period is unreasonable. Comparatively short periods should be used such as 30 years".

Baldock (3) states "Future technology changes (in the next 40 years) may make present day roads obsolete and render more attractive a different type of transportation investment. There is no indication that such changes will jeopardize the billion of dollars now invested in roads. However, discretion requires that present and future beneficiaries carry the requisite costs to retire the investment within a reasonable period of time. This period of time may be termed the analysis period." Baldock recommended an analysis period of 40 years.

Analysis periods adopted in studies of different alternates of highway pavement have ranged from 20 to 40 years.

Additional Highway User Cost Resulting from Maintenance

Time is a valuable commodity to the highway user. Due to the reduction of highway capacity by lane closure for the purpose of resurfacing or maintenance, there is some time lost to road users and also the chance of accidents increases.

Very little research has been conducted to evaluate traffic delay and accident costs resulting from resurfacing and maintenance operations. Generally, a fixed percentage of the maintenance cost is considered to be due to highway user cost (10).

PURPOSE AND PLAN OF RESEARCH

The purpose of this research was to develop a method for predicting the optimum initial service life and the optimum periods of resurfacing for flexible pavements.

The formula recommended by Baldock (3) was used in this study for determining the annual costs and comparison of alternate designs. The pavement design method developed by The Corps of Engineers and presented by Turnbull, Foster, and Ahlvin (17) formed the basis for this analysis. The developed equation by Ulbricht (18) was used to arrive at the total cumulative number of equivalent 18-kip single axle applications in terms of average daily traffic.

Variables included in this research include: (1) subgrade type, (2) initial traffic volume, (3) rate of traffic growth and (4) rate of interest. Solutions were made for: 2-lane highway and 4-lane divided highway, and for analysis periods of 20 and 40 years. The effect of highway user cost resulting from maintenance and resurfacing operations was studied.

PROCEDURE

Regression Technique

Regression technique was used quite often in this study. Following is a brief explanation of it.

Regression technique is a tool by means of which an equation that relates a dependent variable to a number of independent variables, can be obtained (6, 13). The resulting equation that relates a dependent variable to a number of independent variables is usually called a regression equation. A linear regression equation is one which is linear in parameters of the equation, while a non-linear regression equation is non-linear in parameters of the equation.

Several procedures have been developed for the selection of the best regression equation. Methods used in this study were the stepwise regression and the non-linear weighted regression procedures.

The stepwise regression analysis utilized was BMD2R. In this program the most highly correlated independent variable enters into the regression first. The next variable to enter is the one whose partial correlation with the dependent variable is the highest. At every stage variables incorporated into the regression in previous stages are re-examined, by means of comparing the partial F-value of each variable in the regression with a preselected percentage point of the appropriate F distribution. This provides means for evaluation of the contribution made by each variable after the other variables in the equation account for as much variation in the y (dependent variable) as they can. Any variable which provides a non-significant

contribution is removed from the regression. This process is continued until no other variable will be added to the regression nor removed.

The non-linear regression analysis utilized was NONLIN, a revised version of SHARE program no. 3094. This program provides the least squares estimates of the parameters in any equation, or the parameters of any equation are such estimated to result into the minimum sums of squares of the deviations. An initial estimate of the parameters of the regression equation are required, and through iterative procedure the values of the parameter that result in the minimum of squares of the deviations are evaluated.

Average Annual Cost of Highways

Baldock (3) proposed the following equation to compute average annual cost:

$$C = CRF_n \left[1 + E_1 (PWF_{n1}) + E_2 (PWF_{n2}) - \left(1 - \frac{Y}{X} \right) (E_1 \text{ or } E_2) (PWF_{n_c}) \right] + M \quad (1)$$

where

C = average annual cost per mile of highway;

CRF_n = capital recovery factor for an analysis period of n years

and for a given rate of interest;

A = initial construction cost per mile of pavement;

E_1 = first resurfacing cost per mile;

n_1 = years of service life of initial pavement surface;

PWF = present worth factor for n_1 or n_2 years for a given interest rate;

E_2 = second resurfacing cost, per mile;

- n_2 = number of years after construction to year when second resurfacing is placed;
 Y = number of years from time of last resurfacing to end of analysis period;
 X = estimated life of last resurfacing in years, and;
 M = average annual maintenance cost per mile.

For this study the above equation was modified by placing the maintenance cost term (M) inside the bracket. This cost item was evaluated for each year from the time of initial construction to the end of analysis period since traffic loads on a pavement, and deterioration of the pavement due to weathering are subject to change during the analysis period. Maintenance cost depends on both of these factors. Also, highway user costs resulting from maintenance and resurfacing operations are considered. The modified equation used is as follows:

$$\begin{aligned}
 C = CRF_n \bigg[& A + E_1 (PWF_{n1}) + RE_1 (PWF_{n1}) \\
 & + E_2 (PWF_{n2}) + RE_2 (PWF_{n2}) + \dots \\
 & + E_m (PWF_{nm}) + RE_m (PWF_{nm}) \\
 & - \left(1 - \frac{Y}{X}\right) (E_m) (PWF_{nm}) \\
 & + \sum_{i=1}^n M_i (PWF_i) + \sum_{i=1}^n RM_i (PWF_i) \bigg] \quad (2)
 \end{aligned}$$

where

- C = average annual cost per mile of highway;
 CRF_n = capital recovery factor for an analysis of n years and for a given interest rate;
 A = initial construction cost per mile of pavement;
 E_1 = first resurfacing cost per mile;

- n_1 = years of service life of initial pavement surface;
 PWF = present worth factor for $n_1, n_2, \dots$, or n_m years for a given interest rate;
 RE_1 = road user cost due to the first resurfacing per mile;
 E_2 = second resurfacing cost per mile;
 n_2 = number of years after construction to year when second resurfacing is placed;
 RE_2 = road user cost due to the second resurfacing per mile;
 n_m = number of years after construction to year when m^{th} resurfacing is placed;
 RE_m = road user cost due to the m^{th} resurfacing per mile;
 Y = number of years from time of last resurfacing to end of analysis period;
 X = estimated life of last resurfacing in years;
 M_i = maintenance cost during the i^{th} year after construction per mile;
 PWF_i = present worth factor for i years and for a given rate of interest, and;
 RM_i = road user cost due to the maintenance operation during i^{th} year per mile.

Basic components of Equation 2 are (a) initial construction cost, (b) resurfacing costs, (c) maintenance costs, (d) road user costs due to maintenance and resurfacing operations, (e) interest rate, (f) analysis period, and (g) service life of initial pavement surface, and service lives of the resurfacings.

The major purpose of this study was to solve equation 2 for a variety of conditions to determine the service life of the initial pavement surface and the service lives of the resurfacings, that result in the lowest average annual cost.

Structural Design Procedure

The structural design procedure used in this study was the revised pavement design method developed by the Corps of Engineers and presented by Turnbull, Foster, and Ahlvin (17). This procedure evaluates required thickness as a function of equivalent 18,000-lb single axle loads* and California Bearing Ratio of the subgrade. Figure 1 shows the design curves of the Corps of Engineers for flexible highway pavements.

It was assumed in this study that the required thickness of pavement for one 18,000-lb single axle load application is equal to zero. Therefore, the general form of design curves takes the following form:

$$D = C \log W \quad (3)$$

where

- D = pavement thickness in inches;
- W = total number of EAL applications during the design life, and;
- C = coefficient of the equation which is a function of the CBR of subgrade.

* For simplicity, the term "equivalent 18,000-lb single axle loads" will be abbreviated EAL.

FIG. 1 CBR DESIGN CURVES FOR 18,000 LB, SINGLE-AXLE, DUAL WHEEL LOAD APPLICATIONS (FROM TURNBULL, FOSTER, AND AHLVIN, PROCEEDING, INTERNATIONAL CONFERENCE ON THE STRUCTURAL DESIGN OF ASPHALT PAVEMENTS, AUGUST, 1962)

The coefficient C, (the slope of curves) can be estimated from Figure 1 for different values of CBR. From utilizing stepwise regression technique this coefficient was found to be:

$$C = 7.8844 - 8.07189 \log \text{CBR} + 2.20335 \log^2 \text{CBR} \quad (4)$$

The R^2 value, the multiple correlation coefficient, for this analysis was as high as 0.9996. Values of the coefficient C as estimated from Figure 1 and the residuals (the predicted value of C by regression subtracted from the estimated value of C from Figure 1) are shown in Table 1 for different CBR values. The highest value of residual was 0.04773. This value would result in a difference in the design thickness of 0.4773 inches for 10^{10} applications of EAL. The value of 0.4773 is less than the error that would result if the design thickness was to be read from the design curve. The low residual and high R^2 values indicates that the assumptions made were quite reasonable, and hence, Equation 3 takes the following form:

$$D = (7.8844 - 8.07181 \log \text{CBR} - 2.20335 \log^2 \text{CBR}) \log W \quad (5)$$

where

D = pavement thickness, inches;

CBR = subgrade CBR value in percent, and;

W = the cumulative number of EAL applications.

In this study minimum thickness of base and subbase layers were assumed to be 4 and 6 inches respectively. A CBR value of 30 percent was adopted for the subbase material.

Table 1: List of Estimated Values of Coefficient C from Figure 1, and Residuals for Different CBR Values

CBR %	Coefficient as estimated from Figure 1	Residuals
2	5.66	0.00561
3	4.56	0.02456
4	3.82	-0.00365
5	3.30	-0.01871
6	2.94	0.00181
7	2.62	-0.01690
8	2.40	0.00788
10	1.89	-0.01587
12	1.72	-0.02007
15	1.47	0.03095
20	1.16	0.04773
25	0.92	0.01386
30	0.78	0.01110
40	0.60	-0.00793
50	0.50	-0.03046

Minimum Required Thickness of Asphaltic Concrete Surface

The Texas Highway Department has established requirements for minimum thickness of asphaltic concrete surface, based on experience (16). These requisites are shown in Figure 2. Equations 6, 7, and 8 are the results of utilizing stepwise regression analysis made on the data shown in Figure 2 for three types of base materials, Grade 1, Grade 2, and Grade 3.

Grade 1:

$$ds = 1.60649 - 1.78145 \log W + 0.31092 \log^2 W \quad (6)$$

Grade 2:

$$ds = -1.91901 - 0.44729 \log W + 0.2144 \log^2 W \quad (7)$$

Grade 3:

$$ds = -15.51857 + 4.18935 \log W - 0.14027 \log^2 W \quad (8)$$

where

ds = minimum required thickness of asphaltic concrete surface,
inches;

W = total EAL application.

The minimum thickness of surface adopted in this study was 1.9 inches.

Equivalent Axle Load Applications

Several methods have been developed to estimate the number of equivalent axle application in terms of average daily traffic (ADT). The equation developed by Ulbricht (18) for Indiana was adopted for this study. This equation takes the following form:

FIG.2 MINIMUM REQUIRED THICKNESS OF ASPHALTIC CONCRETE SURFACE AS A FUNCTION OF TOTAL 18,000 LB. SINGLE AXLE,LOAD APPLICATIONS (MODIFIED AFTER TEXAS HIGHWAY DEPARTMENT CRITERIA)

$$\begin{aligned}
 W &= (F)(V) \\
 V &= 365 (ADT) \left[\frac{(1+J)^Y - 1}{\ln(1+J)} \right] \\
 W &= 365 (F)(ADT) \left[\frac{(1+J)^Y - 1}{\ln(1+J)} \right] \quad (9)
 \end{aligned}$$

where

- W = the cumulative number of EAL applications;
- F = the equivalence coefficient;
- V = number of vehicles;
- ADT = the initial average daily traffic in one direction;
- J = the annual traffic growth rate, and;
- Y = the number of years for which cumulative number of EAL applications is to be estimated.

Ulbricht, in his study, classified Indiana highways into three classes by traffic weight distribution, and estimated F, the equivalence coefficient for each class. An F value of 0.16 was adopted for this study.

Required Pavement Thickness as a Function of Time

The required thickness of pavement and the minimum required surface thickness can be obtained as a function of time by substituting Equation 9 for W in Equations 5 and 6 respectively. Figure 3 shows an example of the thickness relationships with time for an initial ADT of 1000, rate of traffic growth of 10 percent, CBR of subgrade of 5 percent and Texas Grade 1 base material.

FIG. 3 AN EXAMPLE OF REQUIRED TOTAL PAVEMENT THICKNESS AND MINIMUM REQUIRED SURFACE THICKNESS AS A FUNCTION OF TIME FOR AN INITIAL ADT OF 1000 VEHICLE, RATE OF INCREASE IN TRAFFIC OF 10 PERCENT, AND CBR OF SUBGRADE OF 5 PERCENT

Resurfacing Costs

Resurfacing costs were computed on the basis of thickness of layers placed at each stage, and the unit price of the resurfacing material. The extra surface thickness (major resurfacing or major maintenance) required at any instant of time is equal to the difference between assumed initial design thickness and the required thickness from Figure 1 determined on the basis of traffic up to the time of resurfacing. Figure 4 illustrates the general relationship between age and required thickness (22). In this study the period of resurfacing had always taken the value of the initial design service life of surface, as this was what is being done in practice.

It was assumed in this study that if a resurface was to be placed at intervals greater than 10 years, a seal coat layer was placed on the pavement at the end of 10 years in lieu of the major resurface. Seal coat does not contribute to the structural strength of the pavement but it is applied for one or more of the following reasons (20):

- 1) to prevent the entrance of moisture into the base and subgrade.
- 2) to rejuvenate an old, dry, or weathered surface
- 3) to provide a nonskid surface texture
- 4) to change surface color for visibility or for demarkation purposes
- 5) to supply additional asphalt on the surface for more effective sealing by traffic.

FIG.4 GENERAL RELATIONSHIP BETWEEN AGE AND REQUIRED THICKNESS (AFTER YODER, SELECTION OF SOIL STRENGTH VALUES FOR DESIGN OF FLEXIBLE PAVEMENT)

Routine Maintenance Costs

Several models have been developed to predict routine maintenance expenditures (2, 4, 14). The model developed by Radzikowski (14) was used in this study, since surface maintenance expenditures were of major interest. Most of the other models include methods for estimating shoulder and right of way maintenance.

Four basic factors are considered in the model developed by Radzikowski for the prediction of maintenance expenditure. These factors are: (1) traffic on the section measured in vehicles per day for two lanes of pavement, (2) type of subgrade soil, (3) thickness of the surface, and (4) thickness of the base and/or subbase. Each of these factors are related to maintenance effort index numbers.

Maintenance effort index numbers were estimated for each of these four above factors and for each design. The summation of these four indices represents the surface maintenance effort index of each section. Maintenance expenditure was estimated from its relation with the surface maintenance effort index. Figures 5 through 7 show the maintenance index numbers proposed by Radzikowski. Figure 8 shows the relationship between the summation of index numbers and routine maintenance cost.

Since the study by Radzikowski was done in 1955, it was assumed that he used the 1955 unit-maintenance cost values. It was assumed also that the maintenance cost trends since 1955 are the same as construction cost trends. Using data from Engineering News-Record (7) construction cost trends for the base year 1955 were obtained and the construction cost index for the year 1969 was used to convert the maintenance unit cost from 1955 to 1969. Figure 9 shows the construction cost trends for the base year 1955.

FIG.5 MAINTENANCE EFFORT INDEX AS A FUNCTION OF SURFACE THICKNESS (AFTER RADZIKOWSKI)

FIG.6 MAINTENANCE EFFORT INDEX AS A FUNCTION OF
BASE AND SUBBASE THICKNESS (AFTER
RADZIKOWSKI)

FIG.7 MAINTENANCE EFFORT INDEX AS A FUNCTION OF SUBGRADE CBR (AFTER RADZIKOWSKI)

FIG.8 MAINTENANCE COST AS A FUNCTION OF SURFACE AND BASE THICKNESS, SUBGRADE CBR, AND TRAFFIC VOLUME (AFTER RADZIKOWSKI)

FIG.9 CONSTRUCTION COST TRENDS (FROM ENGINEERING NEWS RECORD)

Equations 10 through 13 relate maintenance effort index to the four basic factors described. Equations 10 and 11 were obtained utilizing stepwise regression analyses on data from Figures 5 and 6. These equations had R^2 values of 1.0000 and .9996, respectively. Equation 15 relates surface maintenance effort index of the section to the annual maintenance cost per 10,000 sq. yd. The R^2 value for Equation 15 was .9998.

$$I_{d_s} = 14.42857 - 2.41501 (d_s) + 0.10187 (d_s^2) \quad (10)$$

$$I_{d_{bs}} = 5.71265 - 0.95354 (d_b + d_{sb}) + 0.04042 (d_b + d_{sb})^2 \quad (11)$$

$$I_s = 9.938 - 6.436 (\log CBR_{sg}) \quad (12)$$

$$I_x = \left(\frac{1}{1000} \right) X \quad (13)$$

$$I = I_{d_s} + I_{d_{bs}} + I_s + I_x \quad (14)$$

$$M = 279.19395 - 3.46509 (I^2) + 0.33537 (I^3) \quad (15)$$

where

I_{d_s} = maintenance effort index for surface thickness;

d_s = surface thickness in inches;

$I_{d_{bs}}$ = maintenance effort index for the base and/or subbase thickness;

d_b = base thickness in inches;

d_{sb} = subbase thickness in inches;

I_s = maintenance effort index for the subgrade condition;

CBR_{sg} = subgrade CBR in percent;

I_x = maintenance effort index for the traffic condition;

- X = the traffic on the section, vehicles per day for two lanes of pavement;
- J = maintenance effort index of the section, and;
- M = annual maintenance cost, dollars per 10,000 sq. yd.

Unit Cost of Paving Materials

Unit cost of bituminous surface, base, subbase, surface treatment, and sealing materials adopted for this study were based on the average unit bid price, obtained from the Indiana State Highway Commission, and are as follows:

Bituminous surface	3743.238	dollars/mile/lane/inch of thickness
base	1415.969	" " " " " "
subbase	1048.178	" " " " " "
surface treatment	3000.953	dollar/mile/lane/layer
seal coat	2173.441	" " " "

Road User Cost Due to Maintenance and Resurfacing Operations

For the purpose of this study, road user costs due to maintenance and resurfacing operations were assumed to be extra costs to road users because of maintenance operations. These extra costs were estimated on the basis of relationships between road user cost and the average speed of traffic in the traffic flow. Accident costs resulting from maintenance and resurfacing operations were not considered.

In this study, it was assumed that specifications would limit the extent of lane closure for each resurfacing operation to 1/2 mile with a duration of closure of 8 hours. For sealing operations, the length of the lane closure would be 1 mile with a duration of closure of 8 hours.

This latter amount was also used for routine maintenance operation. It was also assumed that each section was closed once a year for routine maintenance operation. The shoulder would be used as a traffic lane when one lane was closed on the 2-lane highway. No attempt was made to optimize the extent and the duration of the closure in relation to the traffic.

Relationship Between the Average Speed of Traffic and Traffic Flow.

In this study, the highway types considered were 2-lane and 4-lane divided highways. Relationships between the average speed of traffic and vehicular flow in passenger car equivalents (p.c.e.'s) during both, normal conditions and with one lane closed were established using data from the Highway Capacity Manual (9). The average factor used for conversion of truck traffic to passenger car equivalents was:

$$1 \text{ truck} = 3.58 \text{ p.c.e.}$$

For both of the highway types (2 lane and 4 lane) a lane width of 12-ft. and a shoulder width of 8 ft. were used. The percentage of trucks in this and traffic stream was assumed to be 14% of the total. The highways were assumed to be in level terrain. When one lane was closed for maintenance or resurfacing operations, the distance from traffic lane edge to obstruction was set at zero.

Nonlinear weighted regression analysis was used to arrive at a relationship between the average speed of traffic and the traffic flow. The general form of the model used in these analyses was:

$$V = B_0 + B_1 (v) + B_2 (v^2) + B_3 (v^3)$$

where

V = the average speed of traffic in miles per hour;

v = the traffic flow in passenger car equivalents per hour, and;
 B_0, B_1, B_2 , and B_3 = the parameters of the model.

Using the equation form noted above, B_0 represents the value of the average speed of traffic as the traffic flow approaches zero and B_1 can be calculated as a function of B_2, B_3 and v . The parameters B_2 and B_3 were estimated using the nonlinear weighted regression analysis.

Because the resulting equations were internal to the computer program for forecasting road users costs, no attempt was made to limit the reported equations to a reasonable number of significant figures. Following are the resulted equations:

2-lane highways, normal condition:

$$v = 70 - 3.7643441339 \times 10^{-2}(v) + 1.3541242 \times 10^{-5}(v^2) - 2.86968751 \times 10^{-9}(v^3) \quad (16)$$

R^2 value for this equation was 0.9991

2-lane highways, one lane closed:

$$v = 45 + 7.003349954 \times 10^{-3}(v) - 3.0747339 \times 10^{-5}(v^2) + 1.28845385 \times 10^{-8}(v^3) \quad (17)$$

R^2 value for this equation was 1.0000

4-lane divided highways, normal conditions:

$$v = 70 - 1.1617537335 \times 10^{-2}(v) + 1.9747544 \times 10^{-6}(v^2) - 8.42303439 \times 10^{-9}(v^3) \quad (18)$$

R^2 value for this equation was 0.9976

4-lane divided highways, one lane closed:

$$v = 50 - 1.121901513 \times 10^{-2}(v) - 2.19747544 \times 10^{-6}(v^2) + 2.32506269 \times 10^{-9}(v^3) \quad (19)$$

R^2 value for this equation was 1.0000

where

V = average speed of traffic, miles per hour, and;

v = traffic flow (p.c.e.) in both directions for 2 lane highway and in one direction for 4-lane divided highway.

Figures 10 and 11 show these relations for the types of highways considered in this study.

When traffic flow exceeded capacity it was assumed that the excess vehicles would queue up on the approach to the construction area. As the capacity (service rate) is less than the traffic flow (arrival rate), the queue will increase in length and theoretically the length of the queue will increase to infinity. In the general case, such a condition would not occur as the demand flow would drop below the capacity. Many drivers would not tolerate such large delays and would refuse to join the queue but would find an alternate route. The maximum average waiting time in the queue therefore, would depend on the availability of alternate routes. In the absence of specific information, it was assumed that a reasonable maximum average waiting time in the queue would be 10 and 5 minutes for 2-lane highway and 4-lane divided highway, respectively.

Relationship Between the Road User Cost and the Average Speed of Traffic.

The components of the road user cost are the operating expenditures for fuel, oil, tires, and vehicle maintenance and repair, and allowances for depreciation, time, and comfort and convenience.

The AASHO Red Book provides information which relates road user costs for passenger cars to the average speed of traffic (1). This information is available for 2-lane and divided highways, under free,

FIG.10 AVERAGE SPEED AS A FUNCTION OF TRAFFIC FLOW FOR A TWO LANE HIGHWAY

FIG. 11 AVERAGE SPEED AS A FUNCTION OF TRAFFIC FLOW FOR A 4-LANE DIVIDED HIGHWAY

normal, and restricted operations, and four different gradient classes. Unit costs provided in this report were for the year, 1959.

Data are available in Statistical Abstract of the United States (19) on the cost trends for different commodities; as well as for personal income, gross national product, and personal consumption expenditures on services. For the conversion of these data from the base year 1959, related factors were obtained for the period from 1959 to 1969 and similarly for other base years. The following similarities on cost trends were assumed: fuel and oil to be the same as petroleum and products, depreciation to be the same as motor vehicle and equipments, maintenance and repair to be the same as a combination of 50 percent motor vehicle and equipments and 50 percent personal consumption expenditures on services, time cost to be the same as personal income, and comfort and convenience to be the same as gross national products. Figures A-1, A-2, A-3, A-4, and A-5, in Appendix A show cost trends for petroleum and products, tires, and motor vehicles and equipments and the trends in personal consumption expenditures on services, and personal income and gross national products, respectively.

The factors used for converting the 1959 unit cost to 1969's are as follows: for fuel, 1.052; oil, 1.052; tires, 1.054; maintenance and repair, 1.365; depreciation, 1.010; time, 1.670; and comfort and convenience, 1.7000.

The relations between road user cost and the average speed of traffic under free, normal and restricted operations, for 2-lane highway and divided highway are shown in Figures B-1 through B-6 of Appendix B.

On Figures 10, and 11 the ranges for free, normal, and restricted operations are specified. Using these ranges and the relationship between the average speed of traffic and road user costs for free, normal, and restricted operations the relations between the road user cost and the average speed of traffic were obtained for 2-lane and divided highways, for different gradient classes, and for normal condition and when one lane was closed. Figure 12 shows a general example of relating road user cost to the average speed of traffic when the relations for free, normal, and restricted operations were known. Tables 2 and 3 show the equations resulting from stepwise regression analysis for the road user cost as a function of the average speed of traffic for different gradient classes under normal conditions and when one lane is closed for 2-lane and divided highways. R^2 values obtained for these equations are as shown in the tables.

Figures 13, 14, 15, and 16 show the relation between road user cost and the average speed of traffic for 2-lane and divided highways, under normal condition and when one lane was closed, for different gradient classes. A gradient class of 3-5% was adopted in this study.

Road User Costs Due to Standing Delays and Reduction of Speed.

There is an extra cost associated with vehicle stops, besides that of constant speed operation. This extra cost depends on the approach speed. There are data available in the AASHO Red Book (1) that relate the extra cost per vehicle stop to the standing delay period for different approaching speeds. When the traffic flow exceeds the capacity of the section, queue forms, and the approaching speed is the speed at the capacity of the section which was assumed to be 30 mph in this study.

Table 2: Equations for the Road User Cost as a Function of the Average Traffic Speed for 2-lane Highways

Condition	Gradient (percent)	Equations	No.	R ²
Normal	0-3	$RUC^* = 25.21775 - 0.34123(v)^{**} + 0.00004(v^3)$	(20)	0.9490
"	3-5	$RUC = 10.85570 + 0.56917(v) - 0.01859(v^2) + 0.00016(v^3)$	(21)	0.9500
"	5-7	$RUC = 25.08701 - 0.33841(v) + 0.00005(v^3)$	(22)	0.9956
"	7-9	$RUC = 25.66246 - 0.35281(v) + 0.00005(v^3)$	(23)	0.9957
One Lane Closed	0-3	$RUC = 40.4075 - 1.2433(v) + 0.0141(v^2)$	(24)	0.9995
"	3-5	$RUC = 39.495 - 1.1866(v) + 0.0134(v^2)$	(25)	0.9993
"	5-7	$RUC = 35.280 - 0.81040(v) + 0.0088(v^2)$	(26)	0.9998
"	7-9	$RUC = 32.40 - 0.81040(v) + 0.0088(v^2)$	(27)	1.0000

* RUC = Road User Cost, cents per vehicle mile.

** v = Average Speed of Traffic, miles per hour.

Table 3: Equations for the Road User Cost as a Function of the Average Traffic Speed for Divided Highways

Condition	Gradient (percent)	Equations	No.	R ²
Normal	0-3	$RUC^* = 23.20675 - 0.26597(v)^{**} + 0.00002(v)^3$	(28)	0.9998
"	3-5	$RUC = 23.33263 - 0.26653(v) + 0.00002(v)^3$	(29)	0.9997
"	5-7	$RUC = 25.82212 - 0.42668(v) + 0.00352(v)^2$	(30)	0.9997
"	7-9	$RUC = 25.23348 - 0.39751(v) + 0.00352(v)^2$	(31)	0.9995
One Lane Closed	0-3	$RUC = 31.67329 - 0.14529(v) + 0.00723(v)^2$	(32)	0.9992
"	3-5	$RUC = 31.20000 - 0.71900(v) + 0.00700(v)^2$	(33)	0.9994
"	5-7	$RUC = 31.16486 - 0.71406(v) + 0.00709(v)^2$	(34)	0.9986
"	7-9	$RUC = 31.43914 - 0.72454(v) + 0.00751(v)^2$	(35)	0.9988

* RUC = Road User Cost, cents per vehicle mile.

** v = Average Speed of Traffic, miles per hour.

FIG 12 A GENERAL EXAMPLE OF RELATING ROAD USER COST TO THE AVERAGE SPEED OF TRAFFIC, WHEN THE RELATIONS FOR FREE, NORMAL, AND RESTRICTED OPERATIONS ARE KNOWN

FIG.13 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A TWO LANE HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER NORMAL CONDITIONS FOR SEVERAL GRADIENT CLASSES

FIG.14 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A TWO LANE HIGHWAY AS A FUNCTION OF AVERAGE SPEED AND GRADIENT CLASS WHEN ONE LANE IS CLOSED

FIG.15 ROAD USER COST FOR PASSENGER CARS ON TANGENTS
FOR A 4-LANE DIVIDED HIGHWAY AS A FUNCTION OF
AVERAGE SPEED UNDER NORMAL CONDITIONS FOR SEVERAL
GRADIENT CLASSES

FIG.16 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A 4-LANE DIVIDED HIGHWAY AS A FUNCTION OF AVERAGE SPEED AND GRADIENT CLASS WHEN ONE LANE IS CLOSED

A cost trend adjustment factor of 1.67 was applied to the data available in the AASHO Red Book to convert these costs from 1959 to 1969. This conversion factor was based only on the trends of time cost. Although the components of this cost item includes other costs, the time cost would represent the main portion of it.

The relationship between extra cost per vehicle stop and the standing delay period is linear over the range of standing delay periods beyond 20 seconds. This relationship is shown in Figure 17. Equation 36 relates the extra cost per vehicle stop to the standing delay period over its linear range

$$P = 1.336 + 5.01 t \quad (36)$$

where

P = extra cost in cents per vehicle stop for an approach speed of 30 mph, and;

t = standing delay period in minutes.

As traffic approaches the construction zone, it slows down from the speed on the highway under normal condition to the speed on the construction zone, and vice versa. Claffey's (5) data and his particular solution established a speed change unit value of 0.048 cents plus or minus 0.062 cents. A speed change unit is a plus or minus change in speed of 1 mph. In the absence of any other information, Claffey's value of 0.048 cents was adopted in this study.

Correction Factor for the Extra Turning Maneuver Due to the Lane Closure.

The values of road user cost noted earlier were for open or high type of alinement. For conditions of curved alinement a correction is made by increasing tangent costs in accordance with a correction factor

FIG.17 COST PER VEHICLE STOP VS. TIME OF STANDING DELAY

that depends on the sharpness of the curve and superelevation (1). As different alternates had the same alignment no correction was made, except for the extra turning maneuver, due to lane closure.

It was assumed that the traffic changes lane in a distance of 200 ft. Therefore, the degree of curvature for this maneuver was approximately 4° . The superelevation was obviously zero. Figure 18 shows the relationship between operating costs on curves and on tangents. The dashed line on this figure shows an example of arriving at the correction factor when the average speed of traffic is known. This correction factor should only be applied to the percent of the length of curvature. The percentage of the length of the roadway in the construction area that will be on the curve are approximately 7 and 15, for lane closure lengths of 1 and 1/2 mile respectively.

Considering the factors mentioned the following equations resulted from utilizing stepwise regression analysis:

Length of closure of 1/2 mile,

$$F = 99.12968 + 0.00151 (v^2) \quad (37)$$

R^2 value for this equation was 0.9958

Length of closure of 1 mile,

$$F = 99.595335 - 0.0007 (v^2) \quad (38)$$

R^2 value for this equation was 0.9995

where

F = the correction factor, percent, and;

v = the average speed of traffic, miles per hour.

Figure 19 shows the correction factor for operating cost, as a function of the average speed of traffic for lane closure lengths of 1 and 1/2 miles.

FIG.18 RELATIONSHIP BETWEEN OPERATING COSTS ON CURVES AND OPERATING COSTS ON TANGENTS (SOURCE: REFERENCE 1)

FIG.19 CORRECTION FACTOR FOR OPERATING COST AS A FUNCTION OF AVERAGE SPEED FOR CLOSURE LENGTHS OF 1 AND 1/2 MILES

ANALYSIS

The models described in previous parts were utilized to calculate average annual costs of 2-lane highway and 4-lane divided highways. Programs were written in FORTRAN IV computer programming language. CALCOMP routines and plotter were used to produce the necessary plots of data.

Average annual costs of highways were computed for initial design service lives of the surfaces ranging from two years up to the end of the analysis period. The initial design service life of surface which resulted in the lowest value of the average annual cost was accepted as the best alternate.

Effects of subsoil condition, traffic, interest rate, and analysis period on the result, were studied by solving the problem for subgrade CBR values of 2, 4, 7, 11, and 16 percent; initial average daily traffic values of 10, 50, 100, 1000, 2000, 5000, and 10,000 ADT; annual traffic growth rates of 2, 6, 10, and 14 percent; interest rates of 6, 13, and 20 percent; and analysis periods of 20 and 40 years. The problem was also solved with and without the consideration of the road users costs due to lane closures.

The initial construction cost increased as the initial design service life was increased, there were also sudden rises in this cost item, when base and/or subbase was required (minimum base and subbase thicknesses adopted in this study were 4.0 and 6.0 inches respectively).

The routine maintenance expenditure was a decreasing function of the initial design service life of surface. This expenditure was computed on a yearly basis. Of the factors in the model used for predicting this cost item, thicknesses of surface, base and subbase were subject to change as initial design life of surface was changed.

The thickness factor increased as the initial design service life of surface increased. This resulted in a decrease in routine maintenance expenditure as the initial design service life of surface was increased. The resurfacing expenditure also decreased as the initial design service life increased. Therefore, the greater the initial design service life of surface, the less thickness had to be provided to maintain the pavement function throughout the remaining analysis period.

Cost of sealing was an increasing function of the initial design service life of surface in this problem. The resurfacing interval was always equal to the initial design service life of the surface. It was assumed that if a resurface was to be placed at intervals of time greater than 10 years, a seal coat layer should be placed on the pavement at the end of 10 years. Therefore, up to initial design service life of surface of 10 years, no sealing was required. For initial design service life of surface of 10 years to 20 years, one seal coat layer was needed, and for an initial design service life of surface of 20 to 20 years, two seal coat layers were required etc.

This study was conducted with and without the consideration of road users costs due to lane closures as a component of the average annual cost of highway. Obviously, these cost items increased as the

number of times of lane closures increased. Road user cost due to routine maintenance was the same for all alternates, as it was assumed that each section was closed once a year for this purpose. Road user cost due to major maintenance decreased as the initial design service life of surface (which was also equal to the period of resurfacing) was increased. However, road user cost due to sealing increased as initial design service life of surface was increased since, as explained earlier, the number of times that sealings were required increased as the initial design service life was increased.

For any given initial value of average daily traffic, rate of traffic growth, and rate of interest, the average annual highway cost was the highest in the case of a subgrade CBR value of 2 percent and initial design service life of 2 years among the average annual highway costs for the adopted CBR values and other initial design service lives of surface. Therefore, average annual highway costs were computed as a percentage of this highest value (2% CBR and two year interval) for different CBR values and other initial design service lives average annual cost. The computer plotter was so utilized to produce plots of this percentage of cost of surface, as a function of the initial design service life of surface, and for the subgrade CBR values adopted for this study.

Plots of cost were produced in the same manner for the two and four lane highways, with and without the consideration of road user cost due to lane closures and for analysis periods of 20 and 40 years; the adopted values of average daily traffic; annual traffic rates of growth; and rates of interest.

Figure 20 shows a typical plot produced by the CALCOMP plotter, showing the percentage of the average annual cost of highway to be the appropriate average annual cost of the highway for a subgrade CBR value of 2 percent, and initial design service life of surface of 2 years. The example in Figure 20 is for a 4-lane divided highway with an average daily traffic value of 1000 ADT; annual rate of traffic growth of 2 percent; rate of interest of 6 percent; analysis period of 40 years; and with the consideration of the road users costs due to lane closures.

The function relating the average annual cost of highway to the initial design service life of surface is a one of sequence, since the average annual cost of highway is defined only for the exact time of the initial design service life of surface. There were sudden rises and falls in the average annual cost of highway as the initial design service life of surface was increased. This occurred because of fluxuations in components of the average annual cost of highway with the increase of the initial design service life of surface as described in the previous paragraph. Therefore the produced plots represent the average annual cost of highway as a price-wise linear function of the initial design service life of surface.

Because of the complexity of analyzing the factors that caused the rises and falls, it was assumed that the smooth curves passing about the lower parts of the produced plots represented the relationship between the percentage of the annual cost of the highway to its appropriate average annual cost of highway for a subgrade CBR value of 2 percent and initial design service life of surface of 2 years. The dashed smooth curves on Figure 20 illustrate this assumption through

FIG 20 A TYPICAL PLOT PRODUCED BY THE CALCOMP PLOTTER

visual inspection. That is, initial design service life of surface results in minimum values of average annual cost of a 2-lane highway and 4-lane divided highway. The effects of the length of analysis period, consideration of road user costs due to lane closures, subgrade CBR, initial yearly equivalent 18-kip, single-axle load applications, annual rate of traffic growth, and interest rate were studied.

RESULTS AND FINDINGS

The initial design service life factor which resulted in the minimum average annual cost of 2-lane highway and 4-lane divided highway were determined through visual inspection of the modified plots. Figures 21 through 36 show the optimum initial design service life of pavement surface as a function of the initial yearly EAL. These facts were determined with and without consideration of road users costs resulting from lane closures, different interest rates, subgrade CBR values, traffic rate of growth, analysis periods of 20 and 40 years, and for 2-lane and 4-lane divided highways. The following summarizes the results noted from the inspection of Figures 21 through 36:

- 1) Up to a certain value, the optimum initial design service life remained constant as the initial yearly EAL increased. However, beyond this value the service life increased as a constant rate. The value of the initial yearly EAL at which the initial design service life changes from a constant value to an increasing function of the initial yearly EAL was defined as the critical value of the initial yearly EAL.

The value of the critical initial yearly EAL depended upon the consideration of road user costs due to lane closures, interest rate, traffic rate of growth, subgrade CBR value, and the analysis period. This value decreased as the traffic rate of growth increased, but interest rate decreased. As the analysis

period ~~on~~ subgrade CBR increased the critical value of the initial yearly EAL decreased.

The rate of increase in the initial design service life beyond the critical value of the initial yearly EAL depended on the rate of interest, subgrade CBR value, analysis period, and on the traffic rate of growth. The rate of increase in the initial design service life lessened as subgrade CBR value and/or rate of interest increased.

For a 4-lane divided highway critical values of the initial EAL are higher than those of a 2-lane highway; and the rate of increase in the optimum initial design service life of a 4-lane highway is lower than that of a 2-lane highway. This is particularly true for high CBR values.

- 2) The optimum initial design service life decreased as the interest rate increased. For low subgrade CBR values this was the case for the entire range of the initial yearly EAL. However, for higher subgrade CBR values (only beyond the critical value of the initial yearly EAL) the optimum initial design service life was lower for higher interest rates.
- 3) Analysis with consideration of the road user costs due to lane closures resulted in a decrease of the optimum initial design service life over the total range of the initial yearly EAL for low subgrade CBR values and over the range beyond the critical value of the initial yearly EAL for higher subgrade CBR values. The difference between the optimum initial design service life when road user costs due to lane closures were

considered and when road users costs due to lane closures were not considered was as high as 2 years over the range before the critical initial design service life. Beyond this range the difference was as high as 10 years for an analysis period of 20 years and even higher for the analysis period of 40 years. Beyond the initial design service life this gap decreased. The difference between the initial design service life with the consideration of the road user costs due to lane closures was greater for a 4-lane highway than for a 2-lane highway beyond the critical value of the initial yearly EAL.

- 4) At low subgrade CBR values, before the critical value of the yearly EAL, the optimum initial design service life decreased when the interest rate increased. When road users costs due to lane closures were considered at higher subgrade CBR values, the optimum design service life was approximately the same (about 10 years). In the range beyond the critical value of the initial yearly EAL, the initial design service life decreased as subgrade CBR value increased.
- 5) In the range beyond the critical value of the initial yearly EAL, when road user costs due to lane closures were considered and when they were not considered, the difference between the optimum initial design service life decreased when rate of interest increased.
- 6) The optimum initial design service life in the range before the critical value of the initial yearly EAL was constant and approached 10 years for both 2-lane highways and 4-lane divided

highways and also for the analysis periods of 20 and 40 years. The critical value of the initial yearly EAL is lower for 2-lane highways in the range beyond this value. The optimum initial design service life is lower for 4-lane divided highways and for analysis period of 20 years.

FIG. 21 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 2 PERCENT, ANALYSIS PERIOD OF 40 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 22 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 6 PERCENT, ANALYSIS PERIOD OF 40 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 25 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 2 PERCENT, ANALYSIS PERIOD OF 20 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 26 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 6 PERCENT, ANALYSIS PERIOD OF 20 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 27 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 10 PERCENT, ANALYSIS PERIOD OF 20 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 28 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 14 PERCENT, ANALYSIS PERIOD OF 20 YEARS, AND FOR A 2-LANE HIGHWAY

FIG. 29 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 2 PERCENT, ANALYSIS PERIOD OF 40 YEARS, AND FOR A 4-LANE HIGHWAY

FIG. 30 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 6 PERCENT, ANALYSIS PERIOD OF 40 YEARS, AND FOR A 4-LANE HIGHWAY

FIG. 36 OPTIMUM INITIAL DESIGN SERVICE LIFE OF PAVEMENT SURFACE AS A FUNCTION OF INITIAL YEARLY EQUIVALENT 18-KIP, SINGLE AXLE LOAD APPLICATIONS. ANNUAL RATE OF TRAFFIC GROWTH 4 PERCENT, ANALYSIS PERIOD OF 20 YEARS, AND FOR A 4-LANE HIGHWAY

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

During the conduct of this study the need for research on the following subjects was noted.

1. There is a need to develop a model for predicting highway pavement routine maintenance costs which are directly applicable to the State of Indiana. Data regarding surface condition just prior to maintenance intervals at which routine maintenance is done, could be used to refine the model developed in this study.
2. Additional research is needed in the development of a model for estimating road user costs due to lane closure. Data should be gathered regarding the length and duration of lane closure typical of various types of maintenance operations on the highway. The average length of time drivers will tolerate waiting in a queue when there is a lane closure, should be determined. Average speed of traffic ahead of, and on the maintenance zone should also be evaluated.

BIBLIOGRAPHY

1. American Association of State Highway Officials, "Road User Benefit Analyses for Highway Improvements," 1960.
2. Argentina Ministry of Public Works, "A Long Range Plan for Argentina," 1962.
3. Baldock, R. H., "Determination of the Annual Cost of Highways," Highway Research Board, Highway Research Record No. 12, 1963.
4. Betz, J. M., "Highway Maintenance Costs, A Consideration for Developing Areas," Highway Research Board, Highway Research Record No. 94, 1965.
5. Claffey, P. J., "Characteristics of Passenger Car Travel on Toll Roads and Comparable Free Roads," Highway Research Bulletin No. 306, 1961.
6. Draper, N. R., and Smith, H., "Applied Regression Analysis," John Wiley and Sons, Inc., 1968.
7. Engineering News-Record, "Engineering News-Record Construction Cost Index," McGraw-Hill Co., March 1960, March 1965, and March 1969.
8. Gronberg, C. D., and Blosser, N. B., "Lives of Highways Surfaces - Half Century Trends," Proceedings, Highway Research Board, 1956.
9. Highway Research Board, "Highway Capacity Manual," Highway Research Board Special Report No. 87, 1965.
10. Moyer, R. A., and Lampe, J. E., "A Study of Annual Costs of Flexible and Rigid Pavements for State Highways in California," Highway Research Board, Highway Research Record No. 77, 1965.
11. Oglesby, C. H., "Highway Engineering," (second edition), John Wiley and Sons, Inc., 1963.
12. Oklahoma Department of Highways, "Research Study of Maintenance of Highways in Oklahoma," Bureau of Public Roads, 1968.
13. Ostle, Bernard, "Statistics in Research," Iowa University Press, 1969.

14. Radzikowski, H. A., "Report of the Committee on Maintenance Costs," Highway Research Board Bulletin No. 155, 1956.
15. Road Research Laboratory, Ministry of Transport, "The Cost of Constructing and Maintaining Flexible and Concrete Pavements over 50-years," 1969.
16. Texas Highway Department, "Test Method Tex-117-E," 1964.
17. Turnbull, W. J., Foster, C. R., and Ahlvin, R. G., "Design of Flexible Pavements Considering Mixed Loads and Traffic Volume," Proceedings, 1st International Conference on Structural Design of Asphalt Pavements, University of Michigan, 1962.
18. Ulbricht, E. P., "A Method for Comparing Alternate Pavement Designs," MSCE Thesis, Furdue University, 1967.
19. U. S. Department of Commerce, Bureau of Census, "Statistical Abstract of the United States," 1958, 1959, 1960 and 1961.
20. Woods, K. B., (editor) "Highway Engineering Handbook," Sections 3, 18, and 27, McGraw-Hill, 1960.
21. Work, J. K., "An Economic Replacement Model for Surface Determination," Highway Research Board, 1963.
22. Yoder, E. J., "Selection of Soil Strength Values for Design of Flexible Pavements," Highway Research Board Record No. 276, 1969.

APPENDIX A
FIGURES RELATING TO COST TRENDS

FIG.A-1 COST TRENDS - PETROLEUM AND PRODUCTS (FROM
STATISTICAL ABSTRACT OF THE UNITED STATES)

FIG.A2 COST TRENDS - TIRE (FROM STATISTICAL ABSTRACT
OF THE UNITED STATES)

FIG.A3COST TRENDS-MOTOR VEHICLE AND EQUIPMENT (FROM
STATISTICAL ABSTRACT OF THE UNITED STATES)

FIG.A-4 TRENDS IN PERSONAL CONSUMPTION EXPENDITURES
SERVICES (FROM STATISTICAL ABSTRACT OF THE
UNITED STATES)

FIGA.5 TRENDS IN PERSONAL INCOME AND GROSS NATIONAL PRODUCT (FROM STATISTICAL ABSTRACT OF THE UNITED STATES)

APPENDIX B

FIGURES FOR DETERMINING ROAD USER COSTS

FIG.B-1 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A 2-LANE HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER FREE OPERATION

FIG.B2 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A 2-LANE HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER NORMAL OPERATION

FIG.B-3 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A 2-LANE HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER RESTRICTED OPERATION

FIG.B-4 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A DIVIDED HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER FREE OPERATION

FIG.B.5 ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A DIVIDED HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER NORMAL OPERATION

FIG.B-6ROAD USER COST FOR PASSENGER CARS ON TANGENTS OF A DIVIDED HIGHWAY AS A FUNCTION OF AVERAGE SPEED UNDER RESTRICTED OPERATION