WHEEL LOAD EQUIVALENCIES FOR FLEXIBLE PAVEMENTS

by

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below.

R. A. Jimenez October 27, 1981

R. A. JIMENEZ
Professor of Civil Engineering

Date

To my wife Maria Guadalupe, my daughter Karla, my son Paulo, and the next ones which may arrive.

José de Jesús

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I want to express my appreciation to my advisor Professor Rudolf A. Jimenez for his patience, advice and guidance not only during the development of this thesis but during all my studies in the University of Arizona.

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ABSTRACT

When an engineer needs to design a flexible pavement, he has to deal with different types of vehicles (mixed traffic). There are several methods for the structural design of a flexible pavement. Each one of these methods takes into account the different types of vehicles (axles) in a different way. Usually the way they take into account the mixed traffic is by converting the different axles to a fixed axle used as a base for the system. A structural design method for flexible pavement, developed at the University of Arizona by Jimenez, takes into account five different types of axles to represent the total traffic. These types of axles are: passenger, pick-up, front axle, single axle, and tandem axle.

The objective of this study was the development of equivalency factors for Jimenez' method using a 16,000-pound single axle-dual tire as a base for the system; determine the way in which the modulus of elasticity of the subgrade affects the equivalency factors; and establish the influence of elevation on these factors.

It was found that the modulus of elasticity of the subgrade had a significant effect in the equivalency factors

developed. On the other hand, the influence of elevation was almost insignificant. It was also found that the number of repetitions affects the equivalency factors in a significant way.

CHAPTER 1

INTRODUCTION

One can find several methods developed by various professional groups for the structural design of a flexible pavement. The different methods can be grouped in two categories according to the way and base used for the design of a flexible pavement. The first category corresponds to those groups that use empirical or semi-empirical formulas or expressions derived from field test data. The second category corresponds to those groups that use the structural theory approach for the expressions or formulas using elastic theory to compute the stresses and strains within the pavement system. The design method developed by Jimenez (1, 2) in 1972 at the University of Arizona belongs to the second category.

The Jimenez' design method has the following characteristics:

1. The pavement is considered as a structure composed of three linear elastic layers; asphaltic concrete, granular base, and subgrade.
2. The method takes into account the environmental effects by means of regional factors. The regional

factors depend on the elevation of the site. In Arizona there is a linear relationship between average temperature or rainfall versus elevation.

3. The criteria for design are based on control of cracking of the surface course due to flexural fatigue and of rutting of the pavement due to the excessive repetition of vertical strains at the subgrade interface (2). The stresses and strains are calculated with a computer program developed by CHEVRON.
4. The method is a trial and error method in which the variables are the thickness of asphaltic concrete, and the thickness of the granular base. The ideal design occurs when the percent of fatigue life used by stresses and strains are both 100 or close to 100.

In 1980, Al-Arifi (3) using Jimenez' method developed a series of design charts for flexible pavements in Arizona using different kinds of subgrades and various elevations. The charts were developed for rural interstate highway, 16000-pound single axle-dual tire, and different number of repetitions. One problem these charts have is that they do not take into account the other axles considered by the original design method.

The purpose of this work was to obtain equivalency factors for the different types of axles as functions of a single axle-dual tire. With the equivalency factors, the design of a flexible pavement would become easier than with the computer program. An engineer could save money and time using the equivalency factors with the design charts obtaining results in accordance with the original design method.

The criteria followed the same ones used by the original design method. That is, the percent of fatigue life was used as an indicator of proper design.

CHAPTER 2

LITERATURE REVIEW

This review is concerned with the ways which engineers take into account the different types of vehicles that a pavement will carry during its design life. The most used way in which the different agencies or methods take into account of mixed traffic is to convert all the axles to a particular one used as a base for the system. The concept of equivalency factor or equivalent wheel load factor (EWLF) is not a new idea. One can find several definitions of equivalency factor, for instance, Yoder and Witczak (4) give this definition for EWLF: "The damage per pass caused to a specific pavement system by the vehicle in question relative to the damage per pass of an arbitrarily selected standard vehicle moving on the same system." Scrivner and Duzan (5) have identified three major assumptions on which the load equivalency concept is based. The assumptions are:

1. The effect of any axle load can be expressed in terms of an equivalent number of applications of any selected axle load. For convenience, the selected axle load is designed axle load *a*.

2. The combined effect of all axle loads can be expressed in terms of the combined number of equivalent applications of axle load *a*.

3. The effect of mixed traffic can be introduced into a single load equation for loan <u>a</u> by means of the combined number of equivalent applications of axle load <u>a</u>.

These assumptions imply the existence of an equivalency factor which make possible to account the damage caused to the pavement system for each axle as a function of an arbitrarily selected axle. In 1963, Shook, Painter, and Lepp (6) gave the assumptions in which equivalency application concepts are embodied. They are:

1. Load effects are independent of the shape of the performance vs. load applications curve.

2. Load effects are independent of the order in which loads of different magnitude are applied.

3. The effect of a single application of load Li may be expressed as a constant times the effect of some base load Lb.

4. Equivalency is expressed as the ratio of the number of applications of Lb required to produce the same performance as a single application of Li.

5. Pavement thickness required to maintain a given level of performance is a function of the sum of the applications of mixed axle loads expressed as equivalent applications of Lb.

From the first assumption, it can be concluded that the effect produced to the pavement system by any axle load can not be obtained from a plot of performance vs. repetitions. The second one means that the order in which the loads are applied to the pavement system does not alter the total effect produced in the pavement by the different types of loads. The rest of the assumptions recognize the existence of the equivalency factors. These assumptions were considered as hypothetical by the authors due to "There is no direct experimental evidence to confirm or deny them" (6).

Each one of the structural design methods of flexible pavements has its own equivalency factors according to the concepts of failure it has adopted. For instance, some agencies relate failure with the pavement ridability. The ridability of the pavement is reflected in a number assigned to a pavement depending on the conditions of the pavement. When such a number decrease to a certain value, it is assumed that pavement failure has occured. Other groups relate a pavement failure with the number of repetitions of stresses or strains a pavement can endure (allowable number of repetitions). When the number of repetitions of stresses or strains is greater than the allowable number of repetitions, the failure of the pavement is assumed.

Although the purpose of this thesis is not to analize the different methods adopted by other agencies with regards to the equivalency factors, this chapter will give brief description of the way in which three of the most used design methods convert the different axles to a fixed axle used as a base for the pavement design system.

The methods are:

1. The California Method.
2. American Association of State Highway Officials (AASHO).
3. The Asphalt Institute

Factors Developed by California

The initial effort to design a pavement for mixed traffic was made by California. Shook, Painter, and Lepp (6) quote; "The first effort to design for the effect of mixed trafffic was made by California in 1942." At that time California adopted equivalency factors based on studies of portland cement concrete and also on the number of axles and weights of each vehicle. The base load considered was a 5000-pound wheel. Grumm (7) in California Highways and Public Works, March 1942 showed an example of the way in which the axles were classified and the factors were applied. A portion of that example is reproduced in Figure 1. In this figure, the factors adopted by California at that time correspond to the numbers under column 5 according to the number of axles and weights. In 1948, Hveem and Carmany (8) mention that the method for converting axles was modified by A. M. Nash for more convenient application to traffic census data. With the new data, constants

ROAD VI-KER-4-E

Loadometer Station L-32

Limits: South of Famoso . . . .

Average daily traffic (1940) 6629
Average daily commercial traffic 1940 1442
Est. average daily commercial traffic 1950 2884

Average 2163

2163 x 365 x 10 x 2.88 = 22,737,456 axle loads in 10 years

Wheel Load Groups

	(2)	(3)	(4)	(5)	(6)
1.	4500-5500 . .	10.71% =	2,435,182 x	1 =	2,435,182*
2.	5500-6500 . .	9.61% =	2,185.070 x	2 =	4,370,140*
3.	6500-7500 . .	11.96% =	2,719,400 x	4 =	10,877,600*
4.	7500-8500 . .	6.02% =	1,368,795 x	8 =	10,950,360*
5.	8500-9500 . .	3.40% =	773,074 x	16 =	12,369,184*
6.	9500 and over	0.91% =	206,911 x	32 =	6,621,152*

*Estimated equivalent 5000 pound wheel loads in 10 years

Total estimated equivalent 5000 pound wheel loads in 10 years 47,623,618

Design repetitions (traffic in one direction) . 23,811,809

REMARKS: Loadometer station at Junction of Routes 4 and 33 at Famoso.

Figure 1. Classical Type of Computation of Equivalent 5000-Pound Wheel Load

were developed for each type of commercial vehicle depending upon the number of axles. These constants appear in Table 1.

In comparison of the constants developed, Hveem and Sherman (9) after a study of the AASHO Road Test, gave the following expressions for equivalency factors.

$$T = a\, W^{0.5} r^{0.12} \qquad (1)$$

Where:

T = thickness of the pavement

W = wheel load

r = number of repetitions

a = constant

With this equation, load factors may be calculated for mixed traffic. The procedure is as follows: For $W = 5000$ pound or 5 kips and r_b for wheel load base, the equation (1) becomes:

$$T = a(5)^{0.5} r_b^{\;0.12} \qquad (2)$$

and for an i wheel load equal to Wi assuming the same T, the formula (1) becomes:

$$T = a(Wi)^{0.5} r_i^{\;0.12} \qquad (3)$$

Then, dividing (3) by (2) we have:

$$1 = \frac{a(Wi)^{0.5} r_i^{\;0.12}}{a(5)^{0.5} r_b^{\;0.12}} \qquad (4)$$

Table 1. Equivalent Wheel Load Constants Developed by California

No. of Axles	EWL Constants Year 1948	1963	1967
2	300	280	300
3	700	930	920
4	1400	1320	1320
5	2100	3190	4080
6	1600	1950	2860

or

$$\frac{r_b}{r_i} = Fi = \left(\frac{Wi}{5}\right)^{4.2} \qquad (5)$$

Where:

Fi = wheel load equivalency.

With this expression the constant can be obtained using a loadometer study in which the traffic is divided according to the number of axles and the weights of each vehicle. The constants are obtained in the following way. For each number of axles and the different weights, the equivalent wheel loads (EWL) are obtained multiplying the Fi by the number of vehicles. Then an average of EWL is obtained for each number of axle. Dividing this EWL by the number of axles, an EWL per truck is obtained. Finally the EWL per truck is multiplied by 365 to yield the constants used by California.

The constants developed by California have been changing with time based on new data available (see Table 1).

The equivalency constants for California are based on the assumption that all vehicles are classified by axle type (number of axles) and each axle type may be represented by an average Fi value. It is also assumed that the equivalent wheel load constant are applicable to all highways implying a unique mix distribution. An example of how the constants are used appears in Table 2.

Factors Developed by AASHO

The factors developed by AASHO were derived from a statistical analysis of empirical data based upon the results of the extensive AASHO Road Test conducted in Ottawa, Illinois in the late 1950's and early 1960's. The purpose of this test was to develop expressions for the thickness design of pavements. From the study, AASHO developed its formulas using the concept of serviceability--performance. According to Liddle (10) "The serviceability of a pavement is its ability to provide a satisfactory ride for motor vehicles at a stated time." Performance was determined by the serviceability at the time of construction for all pavements sections. The scale for this serviceability was selected arbitrarily ranging from 0 to 5 for a poor pavement to an excellent pavement. With all data collected, AASHO developed the following basic equation for flexible pavement performance.

$$G = \log \left(\frac{Co-p}{Co-Cl}\right) = \beta\ (\log W - \log p) \qquad (6)$$

Where:

G = a function (the logarithm) of the ratio of loss in serviceability at time t to the potential loss taken to a point where p = 1.5.

Table 2. Application of Equivalent Wheel Load Developed by California

Truck Class by Axle	No. of Trucks/day	X	EWL yearly Constants	=	Yearly EWL
2	679		280		190120
3	344		930		319920
4	295		1320		389400
5	1539		3190		4909410
6	113		1950		220350
	Total annual EWL		=		6029200

β = a function of design and load variables that influence the shape of the p(serviceability) versus W(repetitions) curve.

ρ = a function of design and load variables that denotes the expected number of axle load application to a serviceability index of 1.5.

W = number of axle load applications at end of time t.

p = serviceability at end of time t.

Co = initial serviceability value.

Cl = serviceability level (1.5) at which test sections were removed from test.

The variables β and ρ were found to have the following relationship to load and pavement factors.

$$\beta = 0.4 + \frac{0.081(L_1 + L_2)^{3.23}}{(SN + 1)^{5.19} L_2{}^{3.23}} \tag{7}$$

$$\rho = \frac{10^{5.93}(SN + 1)^{9.36} L_2{}^{4.23}}{(L_1 + L_2)^{4.79}} \tag{8}$$

where:

L_1 = load on one single load axle or on one tandem axle set. (kips)

L_2 = axle code = 1 for single axle = 2 for tandem axle set.

SN = structural number = $a_1 D_1 + a_2 D_2 + a_3 D_3$.

a_1, a_2, a_3 = material strength coefficients determined in the test.

D_1, D_2, D_3 = thicknesses for surface, base and subbase courses-inches.

AASHO considers 18000-pound single axle as a base for the system, so if one uses the equations for a single axle which means $L_1 = 18$ and $L_2 = 1$ then the equation (6) becomes

$$\log W_{18} = 5.39 + 9.36 \log (SN + 1) - 4.79 \log (18 + 1) + \frac{G}{\beta_{18}} \qquad (9)$$

and for $L_1 = X$, $L_2 = 1$ the same equation (6) becomes

$$\log W_x = 5.39 + 9.36 \log (SN + 1) - 4.79 \log (x + 1) + \frac{G}{\beta x} \qquad (10)$$

substracting equation (10) from equation (9) one gets

$$\log \frac{W_{18}}{W_x} = \left(\frac{x + 1}{18 + 1}\right)^{4.79} + \frac{G}{\beta_{18}} - \frac{G}{\beta_x} \qquad (11)$$

or

$$Fx = \frac{W_{18}}{W_x} = \left[\left(\frac{L_1 + L_2}{18 + 1}\right)^{4.79}\right] \left[10^{\left(\frac{G}{\beta} - \frac{G}{\beta_x}\right)}\right] \qquad (12)$$

The most common values for p were 2 and 2.5. With these two values, the value of G can be computed. Since β depends on SN value, AASHO gave different values to SN and with p equal to 2 and 2.5 developed tables for equivalency factors. These equivalency factors are considered the most commonly used in the design of pavements in U.S. A listing of equivalency factor developed by AASHO appears on Table 3 & 4.

Table 3. Equivalency Factors Developed by AASHO for Single Axle and $p_t = 2.5$ (4)

Axle Load (kips)	Structural Number, SN					
	1	2	3	4	5	6
2	0.0004	0.0004	0.0003	0.0002	0.0002	0.0002
4	0.003	0.004	0.004	0.004	0.003	0.002
6	0.01	0.02	0.02	0.01	0.01	0.01
8	0.03	0.05	0.05	0.04	0.03	0.03
10	0.08	0.10	0.12	0.10	0.09	0.08
12	0.17	0.20	0.23	0.21	0.19	0.18
14	0.33	0.36	0.40	0.39	0.36	0.34
16	0.59	0.61	0.65	0.65	0.62	0.61
18	1.00	1.00	1.00	1.00	1.00	1.00
20	2.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.31	9.55	7.94	6.83	6.97	7.79
32	13.90	12.82	10.52	8.85	8.88	9.95
34	18.41	16.94	13.74	11.34	11.18	12.51
36	24.02	22.04	17.73	14.38	13.93	15.50
38	30.90	28.30	22.61	18.06	17.20	18.98
40	39.26	35.89	28.51	22.50	21.08	

Table 4. Equivalency Factors Developed by AASHO for Tandem Axle and p_t = 2.5 (4)

Axle Load (kips)	Structural Number, SN					
	1	2	3	4	5	6
10	0.01	0.01	0.01	0.01	0.01	0.01
12	0.02	0.02	0.02	0.02	0.01	0.01
14	0.03	0.04	0.04	0.03	0.03	0.02
16	0.04	0.07	0.07	0.06	0.05	0.04
18	0.07	0.10	0.11	0.09	0.08	0.07
20	0.11	0.14	0.16	0.14	0.12	0.11
22	0.16	0.20	0.23	0.21	0.18	0.17
24	0.23	0.27	0.31	0.29	0.26	0.24
26	0.33	0.37	0.42	0.40	0.36	0.34
28	0.45	0.49	0.55	0.53	0.50	0.47
30	0.61	0.65	0.70	0.70	0.66	0.63
32	0.81	0.84	0.89	0.89	0.86	0.83
34	10.6	1.08	1.11	1.11	1.09	1.08
36	1.38	1.38	1.38	1.38	1.38	1.38
38	1.75	1.73	1.69	1.68	1.70	1.73
40	2.21	2.16	2.06	2.03	2.08	2.14
42	2.76	2.67	2.49	2.43	2.51	2.61
44	3.41	3.27	2.99	2.88	3.00	3.16
46	4.18	3.98	3.58	3.40	3.55	3.79
48	5.08	4.80	4.25	3.98	4.17	4.49

It is noted that the equivalency factors change for different SN values. This is due to the fact that SN depends on both the properties of the materials and the thicknesses of each layer used in the pavement system.

Factors Developed by the Asphalt Institute

The Asphalt Institute has developed equivalency factors using the results of the AASHO Road Test. Shook and Finn (11) analized the AASHO Road Test data taking into account the following variables:

1. Thickness, a linear combination of the thickness in inches of the surfacing, base and subbase layers.
2. The number of applications of a given axle load to serviceability level to 2.5.
3. Axle load, either single or tandem axle configuration.

They quote that: "The basic relationship between the design variables were obtained by applying multiple linear regression techniques to data from AASHO Road Test." After this study, the following equation for thickness design of a flexible pavement was developed.

$$T = a + b \log W + cL \qquad (13)$$

Where:

a, b, and c are constants

W is the number of repetitions

L is the axle load

From this expression, the equivalency factors can be developed as follows: For L = 18 kips single axle the equation (13) becomes:

$$T = a + b \log W_b + c(18) \tag{14}$$

Where

W_b is the number of repetitions of the 18 kips used as the base for the system.

Now for L = Li the equation (13) becomes:

$$T = a + b \log Wi + c(Li) \tag{15}$$

substracting equation (15) from equation (14) one obtains the equivalency factors expression.

$$\frac{W_b}{Wi} = F_x = 10^{\frac{c}{b}(Li - 18)} \tag{16}$$

The value of $\frac{c}{b}$ found by Shook and Finn (11) was 0.12088, then the equation (16) becomes:

$$F_x = 10^{0.12088(Li - 18)} \tag{17}$$

Where L_i is equal to single axle load or $^{1.14}/_2$ times the gross tandem axle load-kips. The factor $^{1.14}/_2$ is taken because with the 32 kip tandem axle (which is the axle load for tandem) the expression $32 \text{ X } ^{1.14}/_{2}$ is almost the 18 kips single axle. this is $\frac{32 \text{ X } 1.14}{2} = 18.24$ kips.

The Asphalt Institute has a manual (MS-1) for the design of flexible pavements in which a graph for equivalency factors appears (12). This graph has two lines for single axle and for tandem axle respectively. The lines represent the equation (17). A copy of that graph obtained from the manual MS-1 is reproduced in Figure 2.

A comparison between equivalency factors developed by AASHO and the Asphalt Institute appears in Tables 5 and 6.

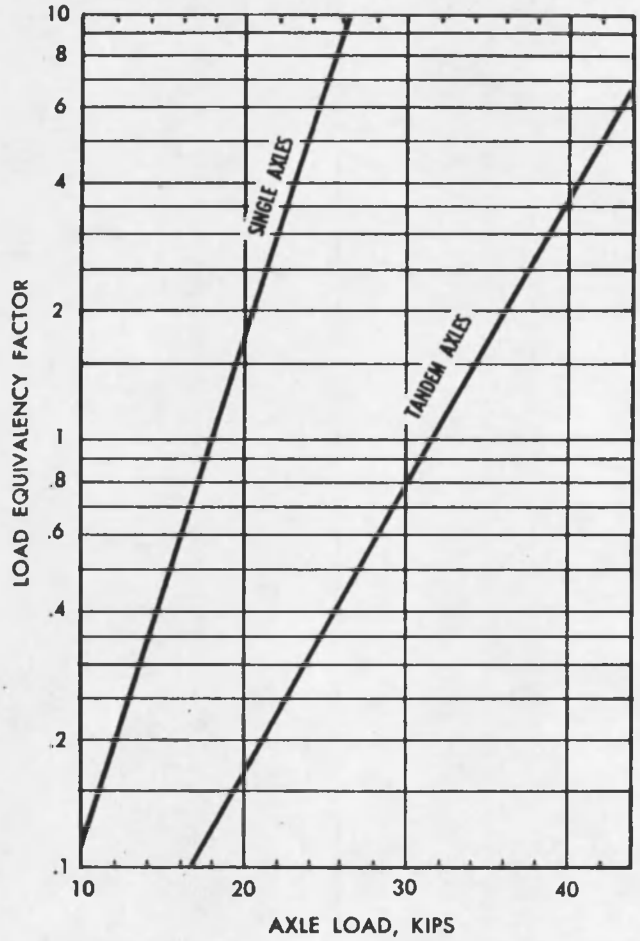

Figure 2. Load Equivalency Factors for Loads Equal to or Greater than 10000-Pounds. -- From Asphalt Institute MS-1

Table 5. Comparison between Equivalency Factors Developed by AASHO and Asphalt Institute for Single Axle

Axle Load (kips)	Asphalt Institute	AASHO (SN = 3)
10	0.11	0.12
12	0.19	0.23
14	0.33	0.40
16	0.57	0.64
18	1.00	1.00
20	1.75	1.49
22	3.04	2.17
24	5.31	3.09
26	9.27	4.31

Table 6. Comparison between Equivalency Factors Developed by AASHO and Asphalt Institute for Tandem Axle

Axle Load (kips)	Asphalt Institute	AASHO (SN = 3)
18	0.12	0.11
20	0.16	0.16
24	0.30	0.31
30	0.78	0.70
32	1.07	0.89
36	2.02	1.38
40	3.80	2.06
44	7.18	2.99

CHAPTER 3

BRIEF DESCRIPTION OF JIMENEZ' METHOD

Jimenez' design method is based on the number of repetitions of stresses and strains a pavement can endure in its design life. The stresses considered are the tensile stresses at the bottom of the surface course, and the strains are the compressive strains at the top of subgrade. Jimenez (1) considered the tensile stresses for controlling surface cracking, and vertical compressive strains to prevent settling of the subgrade which result in rutting of the surface. Also, Jimenez (1) used the stresses and strains with the concept of fatigue in the following way.

Concept of Fatigue Life Used

Fatigue can be defined as the fracture of the pavement due to the repeated application of stresses or strains. Jimenez (2) developed an expression which relates stresses with repetitions. This expressions was:

$$\sigma_t = I_o N^{-b} \qquad (18)$$

Where

σ_t is the radial tensile strength, psi.

N is the number of repetitions of stress σ_t for failure.

I_o and b are constants.

Jimenez (1) gave the values for I_o and b as 1800 and 0.2 respectively. So, the equation (18) becomes:

$$\sigma_t = 1800N^{-0.2} \tag{19}$$

Jimenez (1) also gave an equation to represent some values of compressive strain vs. load applications given by Dorman and Metcalf (13). The expression given by Jimenez was:

$$\varepsilon = 0.0105N^{-0.2} \tag{20}$$

Where

ε = vertical compressive strain.

N = number of repetitions of strain ε to failure.

A computer program developed by CHEVRON was used to find the stresses and strains acting on a given pavement due to an exterior load.

Knowing the stresses and strains imposed on the pavement, one can calculate the allowable number of repetitions the pavement can endure with the two fatigue equations. With all these data, the percent of fatigue life used can be determined as follows.

$$\begin{array}{l}\text{Percent of fatigue life}\\ \text{used for stress or strain}\end{array} = \frac{\text{Actual No. of repetitions}}{\text{Allowable No. of repetitions}} \times 100 \tag{21}$$

Traffic Considerations

Jimenez' design method considers five types of axles with the following characteristics for an interstate rural classification.

1. Passenger car--two wheels, each loaded to 1000 pound (454 Kg.); inflation pressure of 28 psi (1.97 Kg/cm^2); and 70 percent of the average daily traffic (ADT).
2. Pick-up truck--two wheels, each loaded to 1600 pound (726 Kg.); inflation pressure of 32 psi (2.25 Kg/cm^2); and 23 percent of ADT.
3. Front axle--two single wheels, each loaded to 5500 pound (2500 Kg.); inflation pressure of 105 psi (7.39 Kg/cm^2); 10 percent of ADT.
4. Single axle dual wheel--dual wheels spaced 13 in. (0.33 m.) center to center, each wheel loaded to 4000 pound (1820 Kg.); inflation pressure of 105 psi (7.38 Kg/cm^2); 25 percent of ADT.
5. Tandem axle dual wheel--two axles spaced 48 in. (1.22 m.) center to center, each wheel loaded to 4000 pound (1820 Kg.); inflation pressure of 105 psi (7.38 Kg/cm^2); 22 percent of ADT.

The percentages correspond to a rural interstate highway in Arizona. They were obtained by a study of loadometer data conducted by Jimenez (2). From the same study and with the 85 percentile of the laods reported, the loads for each type of axle were determined.

Environmental Effects

Jimenez' design method takes into account the effect of temperature and rainfall with a correction factor. This correction factor is applied to the modulas of elasticity of the surface course (E_1) to account for the effect of temperature. A different correction factor is applied to the modulas of elasticity of the subgrade (E_3) to account for the effect of rainfall. This correction factor is obtained from a regional factor effect established by AASHO. The correction factor is expressed in function of the SN as follows:

$$CF = \frac{SN}{SN_c} = RF^{0.146} \qquad (22)$$

Where

CF = correction factor

RF = regional factor

SN = structural number as defined before

SN_c = corrected structural number due to RF

Jimenez (1) found a linear relationship between elevation and regional factor and between rainfall and regional factor.

With all the data described before, Jimenez (1, 2) developed a computer program called ASPDSN for the design of flexible pavement. This design method, as was mentioned before, considers five different types of axles and up to the present it is necessary to use the five different types of axles, the regional factor and the modulus of elasticity of the subgrade when using the computer program ASPDSN.

CHAPTER 4

EQUIVALENCY FACTORS FOR JIMENEZ' METHOD

As mentioned before, Al-Arifi (3) developed design charts for flexible pavements in Arizona. Each one had four different curves for different number of repetitions of a single axle. The curves have two sections, a curved section and a straight section. The curved section corresponds to a zone in which the failure occurs due to the repetition of vertical strains applied on the top of the subgrade, the straight section corresponds to a zone in which the failure occurs due to the repetition of tensile stresses at the bottom of the surface course (see Fig. 3). The points on the curves correspond to a thickness combination in which a 100 percent of fatigue life is used. The juncture corresponds to a balance design between cracking and rütting.

With the use of the charts, several combinations of thicknesses of H_1 and H_2 for each curve were selected. Then, the ASPDSN computer program was used to find the stresses and strains imposed on the pavement. These stresses and strains were computed by use of the ASPDSN which was run with the following data: modulus of elasticity of surface, base, and subgrade, the regional factors, the

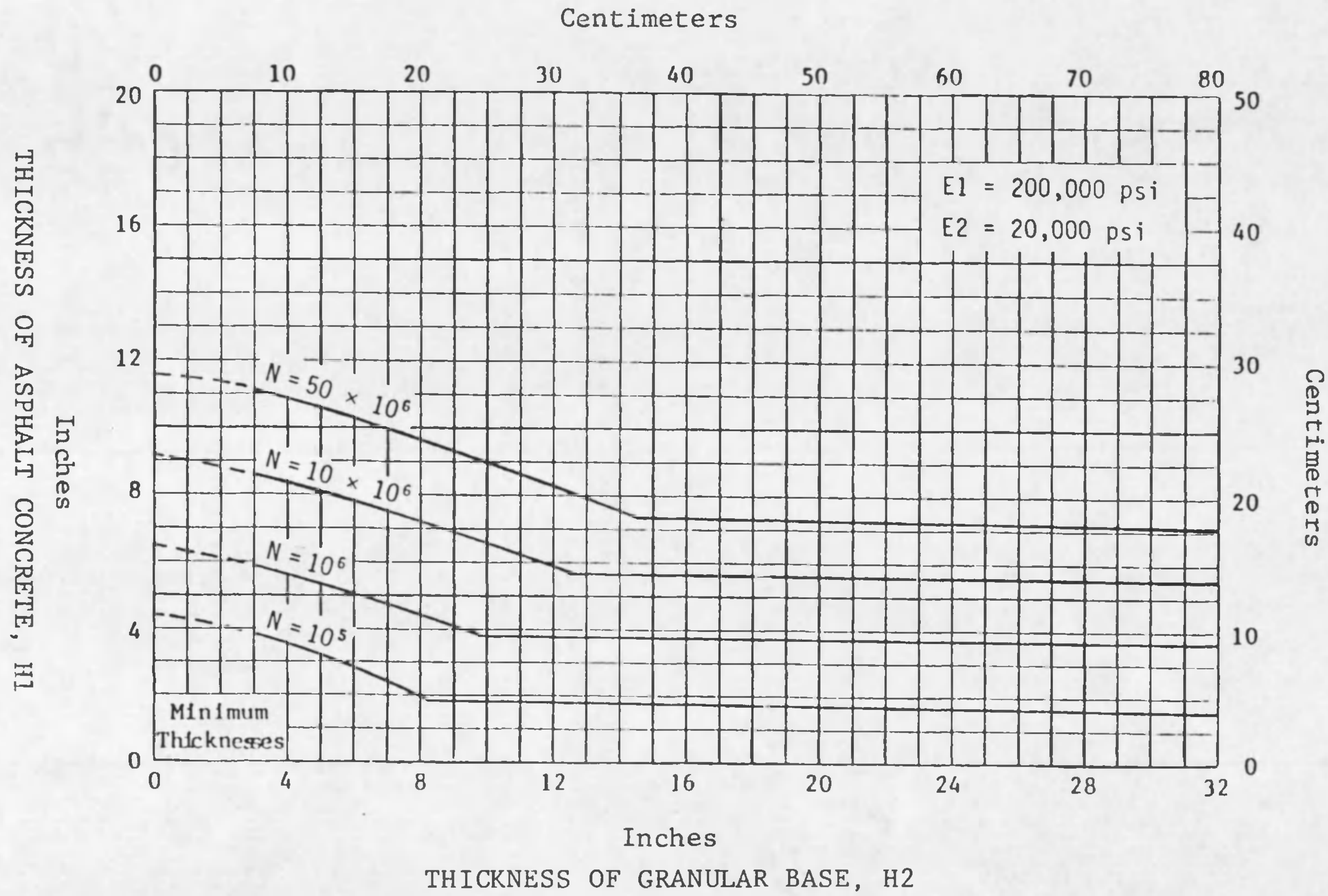

Figure 3. Design Curves for 16,000 Pound Single-Axle Load, Elevation = 1000 Feet, Subgrade Modulus (E_3) = 10,000 PSI. -- After Al-Arifi

exponent of the fatigue equations, the constant of the fatigue equation, and the thicknesses of surface and base course as input data. The axle used for the combinations of thicknesses was the single axle-dual tire with the number of repetitions used in the design of the curves. After running the ASPDSN program with the data mentioned before, in the output of the program appears the stresses and strains applied to the pavement for each type of axle considered by the Jimenez' method. The following step was to get the allowable number of repetitions for each type of axle. Such number also appears in the output of the ASPDSN program. This number is computed using the fatigue equations (19) and (20). Using the percent of fatigue life equation (21) and assuming a 100 percent of fatigue life used, yields the allowable number of repetitions equal to the actual number of repetitions. Next, with the number of repetitions of single axle-dual tire corresponding to the number of repetitions of the curves of the design charts divided by the number of repetitions to failure of each axle, the equivalency factors were obtained for each one of the combinations of thicknesses used. That is:

$$Fi = \frac{\text{actual No. of repetitions of the reference axle}}{\text{actual No. of repetitions of axle i}} \qquad (23)$$

Where: Fi = equivalency factor for any i axle (front or tandem axle). Jimenez (14) was the first one in using the equivalency factor based on fatigue. Although he used the term Destructive Ratio, the meaning is the same as equivalency factor.

After the computation of each Fi for each axle at the different points of the curves for each chart, the equivalency factors were separated according to the cause of failure in the pavement; that is, failure due to the repetitions of stresses or strains.

At this point it is necessary to mention that the axles corresponding to passenger car and pick-up were neglected because the effects of these two axles on fatigue life of a pavement is very small. In all trials run, the fatigue life used by the two axles mentioned was less than one percent.

In analyzing the equivalency factors of the four repetition curves of each chart, it was necessary to divide them into three groups due to the similarity between the equivalency factors corresponding to the curves of 10^5 and 10^6 repetitions, and between the curves of 10×10^6 and 50×10^6 repetitions. The zone between the curves for 10^6 and 10×10^6 repetitions was the third zone. An example of these variations and similarities appear in Table 7. All this was done in the zone corresponding to the zone in which the cause of failure was the repetition of strains in the top of

Table 7. Equivalency Factors Corresponding to Different Points of the Four Curves of a Design Chart

Axle Type	Equivalency Factors for the Strain Zone Repetitions			
	10^5	10^6	10×10^6	50×10^6
	1.69	1.06	0.56	0.35
FA	1.62	0.56	0.34	
	1.42			
	0.85	0.85	0.97	1.05
TA	0.95	0.83	0.95	1.06
	0.98	0.84	1.00	1.10
			1.02	1.21

the subgrade since the zone in which the failure is caused due to the repetition of stresses was treated separately.

The next step was to obtain the average of the equivalency factors for front-axle and tandem-axle in order to compute the equivalent number of single axle (ESA). With the ESA, the percent of fatigue life used was computed using the following equation:

$$\text{percent of fatigue life used} = \frac{100 \times N}{(0.0105)^5} \varepsilon^5 \qquad (24)$$

Where

ε = strain caused to the subgrade for the axle in question.

N = actual No. of repetitions of strain.

The strains were calculated with the ASPDSN program for each combination of thicknesses. The percent of fatigue life obtained was compared with the percent of fatigue life used by the three axles acting separately. The ESA was computed by using the equivalency factors developed multiplied by the corresponding number of repetitions for each axle.

In the first trial, the amount of fatigue life used by all axles of the mixed traffic and the amount of fatigue used by the equivalent single axle were different and some adjustments were made to the equivalency factors until both percentages were almost the same. The adjustments were made with a trial and error method. After these adjustments were made, the differences between the two amounts of fatigue life used were of the order of an average of 0.5 percent to an average of 7.0 percent between them. An example will illustrate the procedure followed in the process as shown in Table 8.

For the first trial, we tried:

$$F_{fa} = \frac{\Sigma F_{fa}}{3} = 3.17$$

$$F_{ta} = \frac{\Sigma F_{ta}}{3} = 0.95$$

Where

F_{fa} = average equivalency factor for front axle

F_{ta} = average equivalency factor for tandem axle

The data for the example were as follows:

Four lane rural interstate highway

Present average daily traffic (ADT) = 60 vpd both directions

50/50 directional split

90/10 lane split

10 years design period

ADT after 10 years = 64 vpd

Modulus of elasticity of surface course (E_1) = 200,000 psi

Modulus of elasticity of granular base (E_2) = 20000 psi

Table 8. Equivalency Factors for Strain Zone at Two Different Number of Repetitions

Axle Type	Equivalency Factors for Strain Zone Repetitions	
	10^5	10^6
FA	3.76	2.22
	3.52	
TA	1.05	0.83
	0.97	

Modulus of elasticity of upgrade (E_3) = 15000 psi

Elevation = 1000' (Regional Factors of 0.8 and 1.0)

The design traffic was computed as follows:

$$\text{design traffic} = \left(\frac{60 + 64}{2}\right) \times 0.9 \times 0.5 \times 10 \times 365$$

$$\doteq 101,835 \text{ vehicles}$$

The total number of passes of each type of axle, was calculated using the percentages given by Jimenez (2) for a four-lane interstate highway which was mentioned before.

Front axle (FA) = 101,835 x 0.10 x 1 = 10183

Single axle (SA) = 101,835 x 0.25 x 1 = 25458

Tandem axle (TA) = 101,835 x 0.22 x 2 = 44807

The factor of 2 for tandem axle corresponds to a two passes for each tandem axle.

The equivalent single axle (ESA) was calculated with the average equivalency factors obtained before and with the amounts of front axle and tandem axle computed.

$$ESA = 10183 \times 3.17 + 25458 + 44807 \times 0.95 = 100304$$

$$\simeq 10^5 \text{ passes}$$

From Figure 4 and from the curve corresponding to a 10^5 repetitions, a thickness design was chosen. The thicknesses for h_1 and h_2 were: h_1 = 2.7" and h_2 = 4.0". With all the data mentioned before, the ASPDSN program was run and the output results are shown in Tables 9 and 10. The ASPDSN program

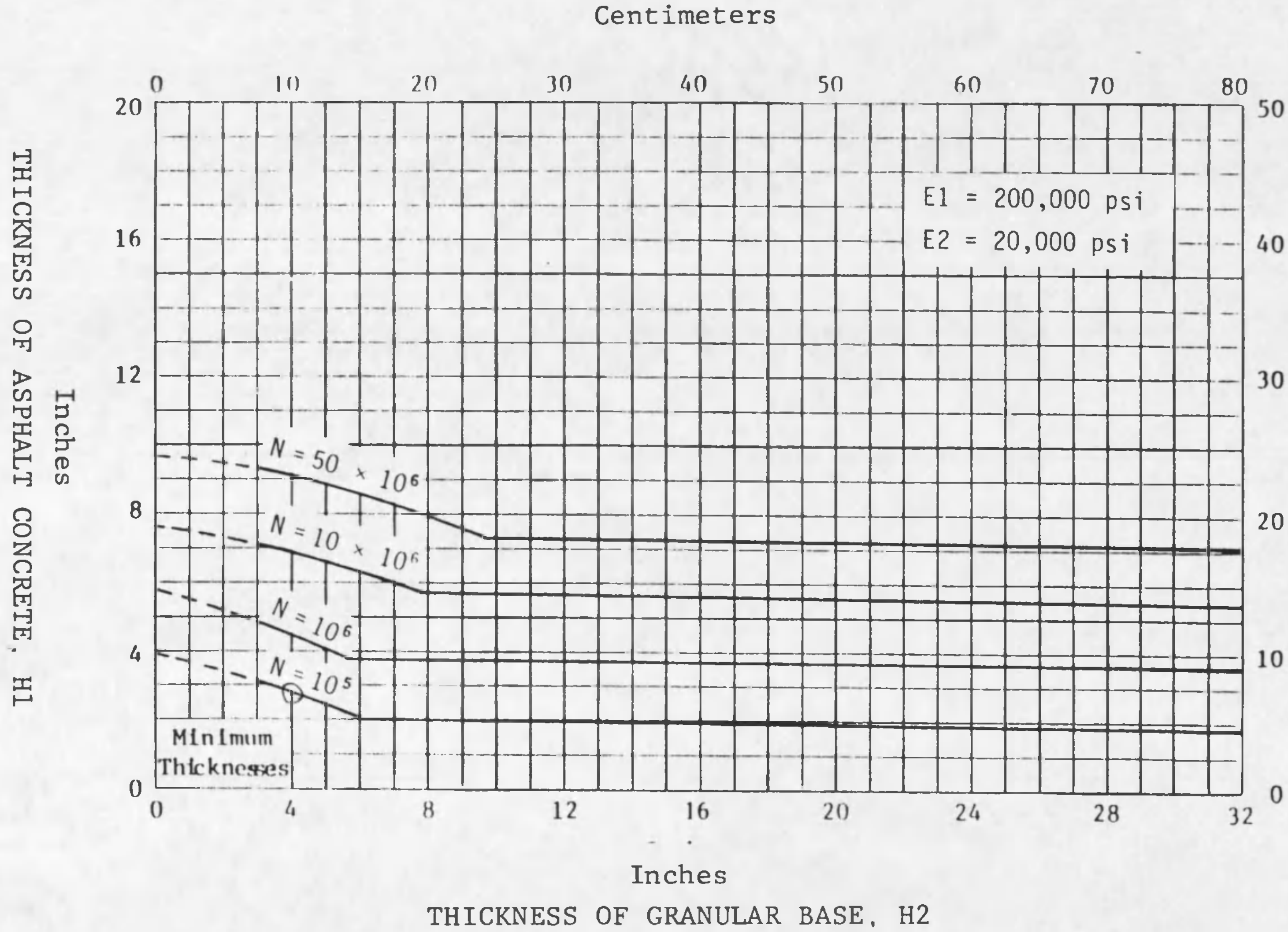

Figure 4. Design Curves for 16,000-Pound Single-Axle Load, Elevation = 1000 Feet Subgrade Modulus (E_3) = 15,000 PSI. -- After Al-Arifi

Table 9. Stresses and Strains Applied to the Pavement with Thicknesses of h_1 = 2.7 Inches and h_2 = 4.0 Inches

Axle Type	Radial Stress psi	Vertical Strain At W.C.	At A.C.
FA	190	0.00137	NA
SA	155	0.00107	0.000723
TA	155	0.00106	0.000717

Table 10. Percent of Fatigue Life Used by SA at N = 10^5 Repetitions with h_1 = 2.7 Inches and h_2 = 4.0 Inches

Axle Type	Percent of Fatigue Life Used For Stress	For Strain At W.C.	A.C.
SA	47.69	108.51	15.47

was run again with the same data but this time with the number of passes corresponding to a front, single and tandem axles. The output of the program gave the results shown in Table 11. It was noted that $108 \simeq 113$ but then comparing the percentages of several points in the curves, an adjustment was made with the following results:

$F_{fa} = 3.40$, $F_{ta} = 0.95$

A new total vehicular traffic was selected for simplicity when using the curves of the design charts. The same procedure was followed in the zone corresponding to failure caused by repetitions of tensile stresses. The same procedure was used when large values of ADT were considered and a transitive zone was noted.

The equivalency factors obtained are given in Table 12. The equivalency factors have been separated according to the total vehicular traffic in the design life of a pavement. The equivalency factors corresponding to the lines marked with an a letter should be used when the total traffic is greater than or equal to the traffic of column 3 but less than the traffic of column 5.

The equivalency factors corresponding to the zone in which the failure is caused by the repetitions of tensile stresses in the bottom of the asphaltic course were divided in two groups according to the total traffic in the design

Table 11. Percent of Fatigue Life Used by FA, SA, and TA with Their Respective Number of Repetitions Using $h_1 = 2.7$ in. and $h_2 = 4.0$ in.

Axle Type	Percent of Fatigue Life Used		
	For Stress	For Strain	
		At W. C.	At A. C.
FA	13.30	38.39	NA
SA	12.02	27.89	3.93
TA	21.15	46.84	6.63
Totals	46.47	113.12	10.56

Table 12. Equivalency Factors for the Zone of Failure Caused by Strains

Elevation	E_3	Used with Total Vehicular Traffic			Equivalency Factors	
Ft	psi	Less than	a	Greater or equal to	FA	TA
1	2	3	4	5	6	7
1000	2000	3700000			3.36	1.16
1000	2000		a		0.32	1.50
1000	2000			7500000	0.28	2.27
1000	6000	4000000			1.10	0.85
1000	6000		a		0.42	0.85
1000	6000			10500000	0.42	0.95
1000	10000	3500000			2.25	0.90
1000	10000		a		1.00	0.84
1000	10000			11500000	0.25	0.83
1000	15000	3500000			3.40	0.95
1000	15000		a		0.25	0.83
1000	15000			12500000	0.25	0.83
3000	2000	2750000			0.40	1.16
3000	2000		a		0.29	1.54
3000	2000			6250000	0.28	2.27
3000	6000	4250000			1.08	0.80
3000	6000		a		0.50	0.80
3000	6000			10500000	0.45	1.06
3000	10000	3500000			2.11	0.86
3000	10000		a		0.45	0.75
3000	10000			12500000	0.25	0.83
3000	15000	3000000			3.49	1.08
3000	15000		a		0.25	1.08
3000	15000			11500000	0.25	0.83
6000	2000	3500000			0.39	1.17
6000	2000		a		0.30	1.54
6000	2000			8000000	0.28	2.27
6000	6000	3750000			1.23	0.87
6000	6000		a		0.40	0.87
6000	6000			12000000	0.40	1.10
6000	10000	3750000			2.25	0.90
6000	10000		a		0.20	0.85
6000	10000			12500000	0.22	0.90
6000	15000	3000000			3.25	0.98
6000	15000		a		1.75	0.78
6000	15000			11500000	0.25	0.81

life of the pavement. The equivalency factors for this zone appear in Table 13.

The equivalency factors were tested for each point of the different curves of each chart and the results found were very close to the results obtained using all the axles of mixed traffic of the original design.

It was noted that the elevation affected the equivalency factors in a very slight manner. That is, for all types of elevations studied, the equivalency factors remained almost constant for similar conditions of E_3. It was also noted that the subgrade modulus of elasticity, E_3, affected the equivalency factors in a significant way. Finally, the strength of the pavement system was also a factor that affected the equivalency factors obtained. This fact was represented by the number of repetitions applied to the pavement system.

A comparison between equivalency factors developed by AASHO and the equivalency factors for Jimenez' method was made and appears in Table 14. The SN values were determined using $a_1 = 0.44$ and $a_2 = 0.14$. From this Table it can be seen that AASHO has only one equivalency factor for each SN meanwhile the Jimenez method has two different equivalency factors. This difference is due to the fact that AASHO does not distinguish between the type of failure and Jimenez' method does.

Table 13. Equivalency Factors for the Zone of Failure Caused by Stresses

Elevation FT	E_3 psi	Used with Total Vehicular Traffic: Less than	Used with Total Vehicular Traffic: Greater or Equal to	Equivalency Factors: FA	Equivalency Factors: TA
All Cases	All Cases	550000		2.15	1.00
			550000	4.00	1.00

Table 14. Equivalency Factors for Jimenez' Design Method Compared with AASHO Factors

	Axle Load	Stress	Strain	AASHO p = 2.5
SN = 5.88 h_1 = 7.0" h_2 = 20.0"	FA[1] TA[1]		0.28 2.27	0.13 (0.21)[2] 0.83
SN = 4.27 h_1 = 7.0" h_2 = 8.5"	FA TA		0.25 0.83	0.15 (0.23)[2] 0.88
SN = 3.70 h_1 = 6.5" h_2 = 6.0"	FA TA		3.40 0.95	0.16 (0.25)[2] 0.89
SN = 3.20 h_1 = 2.5" h_2 = 15.0"	FA TA		0.40 1.16	0.17 (0.26)[2] 0.89
SN = 5.88 h_1 = 5.5" h_2 = 24.7"	FA TA	4.00 1.00		0.13 (0.21)[2] 0.83
SN = 4.27 h_1 = 5.6" h_2 = 12.9"	FA TA	4.00 1.00		0.15 (0.23)[2] 0.88
SN = 3.70 h_1 = 5.6" h_2 = 8.8"	FA TA	4.00 1.00		0.16 (0.25)[2] 0.89
SN = 3.20 h_1 = 2.0" h_2 = 16.6"	FA TA	2.15 1.00		0.17 (0.26)[2] 0.89

1 FA = 11,000 pounds and TA = 32,000 pounds
2 The values in parenthesis are for a SA reference of 16,000 pounds

CHAPTER 5

USE AND EXAMPLES OF THE EQUIVALENCY FACTORS FOR PAVEMENT DESIGN

In this chapter, two examples will be presented to illustrate the way in which the equivalency factors should be used.

EXAMPLE 1. Design for a four-lane, rural, interstate highway at an elevation of 6000'. The data for the example were taken from an actual Arizona Department of Transporation (ADOT) design problem.

20 years design period with 1980 as a base year.

ADT_{1980} = 11160 vpd. both directions

ADT_{2000} = 18300 vpd.

Directional split 50/50

Lane split 90/10

Modulus of elasticity of asphaltic concrete

(E_1) = 200000 psi.

Modulus of elasticity of granular base (E_2) = 20000 psi.

Modulus of elasticity of subgrade (E_3) = 6000 psi.

The total traffic for the design was computed as follows:

$$\text{Total traffic} = \left(\frac{11160 + 18300}{2}\right) \times 0.5 \times 0.9 \times 20 \times 365$$

$= 48388050$ vehicles

For the conditions of E_3 and elevation given, the following equivalency factors for strain and stress zone were used.

For strain. $F_{fa} = 0.40$ and $F_{ta} = 1.10$ (From Table 12).

For stress. $F_{fa} = 4.00$ and $F_{ta} = 1.00$ (From Table 13).

Using the equivalency factors, the ESA was computed as follows.

For strain. $\text{ESA} = 48388050(0.10 \times 0.40 + 0.25 + 0.22 \times 2 \times 1.10)$

$= 37452351$ repetitions (3.75×10^6).

For stress. $\text{ESA} = 48388050(0.10 \times 4.00 + 0.25 + 0.22 \times 2 \times 1.0)$

$= 52742974$ repetitions (53.0×10^6).

As can be seen, neither one of those two ESA lai on a curve of Figure 6 which corresponds to this example. For this reason, it is necessary to interpolate between two curves. The interpolation was made using a semilog scale as was mentioned by Al-Arifi (3).

The following Figures 5 and 6 illustrate this interpolation. The interpolation may be done horizontally or vertically. Both ways were used with the same results. Also, it was found that the interpolation could be used

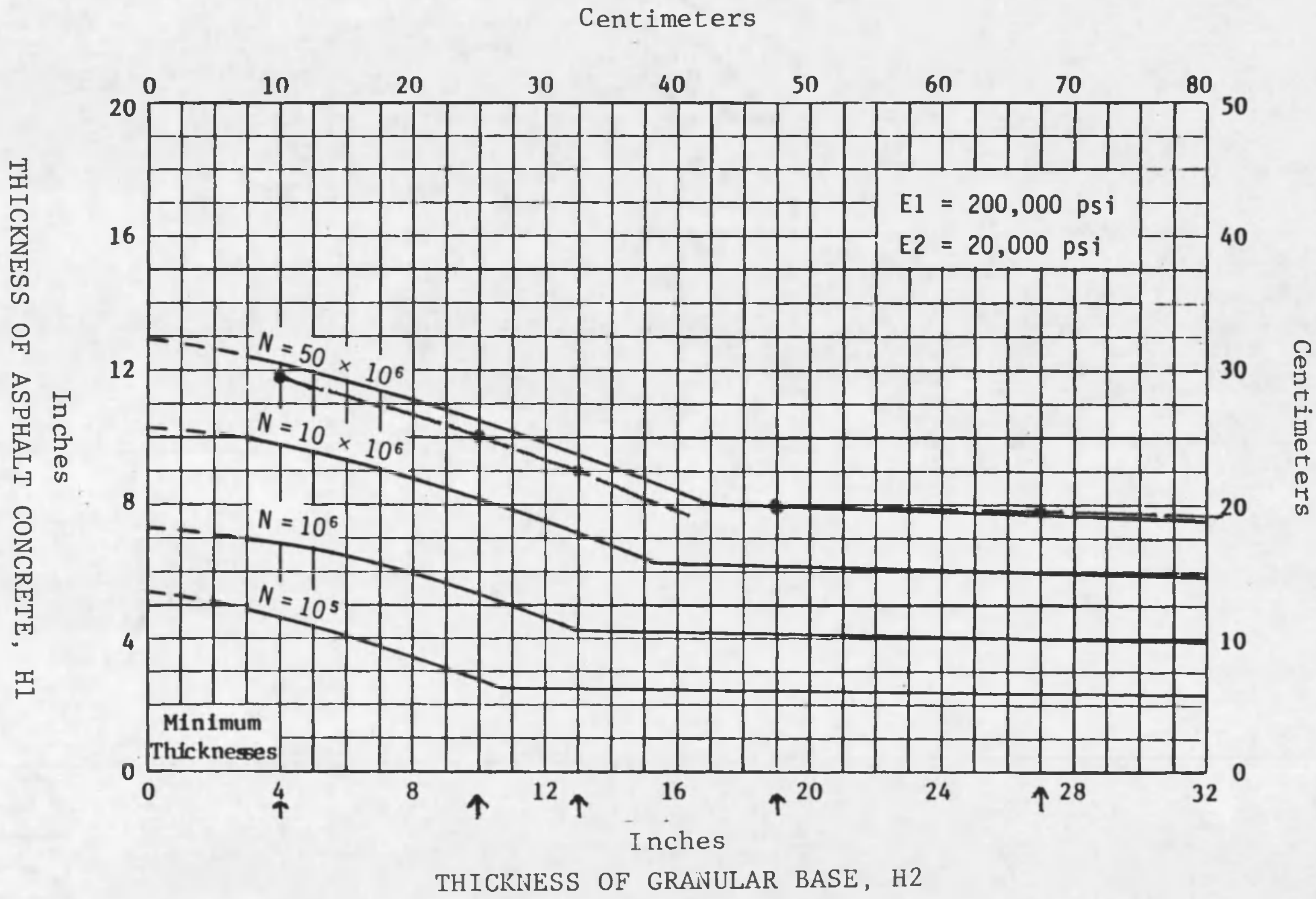

Figure 5. Design Curves for 16,000 Pound Single-Axle Load, Elevation = 6000 Feet Subgrade Modulus (E_3) = 6000 PSI. -- After Al-Arifi

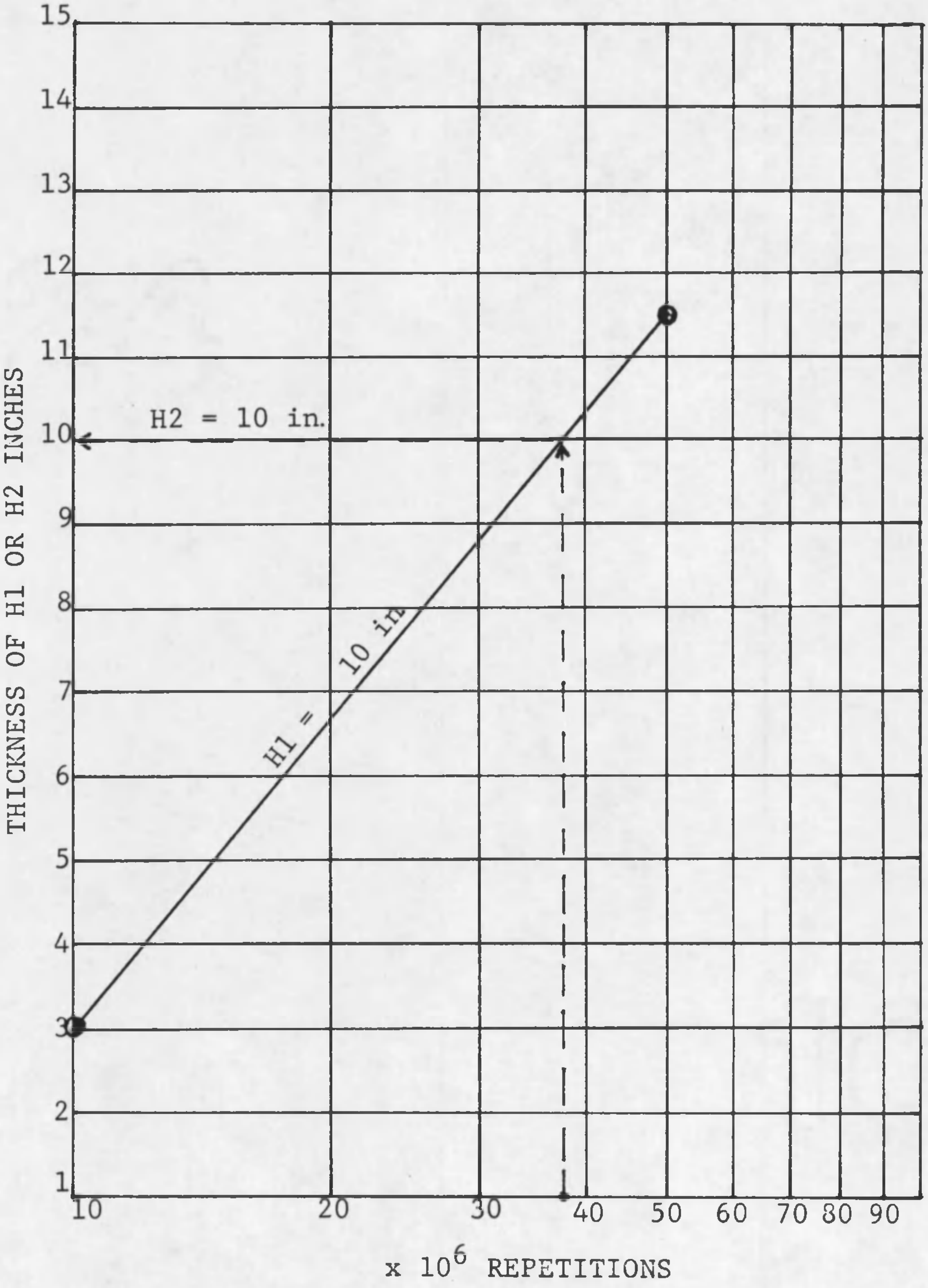

Figure 6. Interpolation Chart for Example 1.

between any two curves. The procedure followed in the interpolation was: For the horizontal interpolation, choose a thickness of h_1 which crosses the curves greater and smaller than design number, in this case, the curves for 10×10^6 and 50×10^6 repetitions. For instance, $h_1 = 10.00$ in. with h_1 chosen we evaluate h_2 for 10×10^6 and 50×10^6 repetitions. This is $h_2 = 3.0$ in. for 10×10^6 and $h_2 = 11.5$ in. for 50×10^6 repetition. Plot as in Figure 6 and join the two points with a straight line. Next, with 37.5×10^6 repetitions we intercept the line and on the other scale we get h_2 for the h_1 chosen. In this case $h_2 = 10.0$ in. The procedure was repeated as was needed with other values of h_1 to establish the location of the curve for $N = 37.5 \times 10^6$ repetitions. In the vertical interpolation the thickness chosen was $h_2 = 4.0$ in. and the thickness found was $h_1 = 11.8$ in. The technique was the same used in the horizontal interpolation. With the points obtained (h_1's and h_2's) for 37.5×10^6 repetitions, we can draw the corresponding curve for this number of repetitions following the shape of the other curves. The acceptable combinations of thicknesses were:

	Strain Zone			Stress Zone	
h_1	11.8	10.0	9.0	8.0	7.8
h_2	4.0	10.0	13.0	19.0	27.0

With each one of these points, the ASPDSN program was run using the ESA of 37.5×10^6 repetitions. The output of the program is shown in Table 15. The same data with the five standard axles were used in the next time the ASPDSN program was run with the following data.

Pass = 48388050 x 0.70 x 1 = 33871635

2P = 48388050 x 0.23 x 1 = 11129252

FA = 48388050 x 0.10 x 1 = 4838805

SA = 48388050 x 0.25 x 1 = 12097012

TA = 48388050 x 0.22 x 2 = 21290742

The output of the ASPDSN program is shown in Table 16.

From analyzing the results of the output of the ASPDSN program for SA only and for mixed traffic, a selection of h_1 and h_2 was made according to the percent of fatigue life used. That is, the combination which was more in accordance with the ideal design was chosen. For the design with SA only, the thickness was: h_1 = 9.0", and h_2 = 13.0". The same combination of thickness resulted for the design using mixed traffic. This indicates that the equivalency factors developed can be used with results very close to the original design method. The differences between the results of the ASPDSN program with ESA and with

Table 15. Percents of Fatigue Life Used by SA at 37.5 x 10^6 Repetitions Using Different Combinations of h_1 and h_2.

ASPDSN Thicknesses h_1	h_2	Percent of Fatigue Life Used For Stress	For Strain At W.C.	At A.C.
11.8	4.0	16.20	57.70	100.19
10.0	10.0	26.62	57.69	105.06
9.0	13.0	42.99	59.76	103.51
8.0	19.0	96.16	47.25	67.48
7.8	27.0	91.66	11.71	12.82

Table 16. Totals of Percents of Fatigue Life Used by the Five Different Axles Considered by Jimenez' Method.

ASPDSN Thicknesses h_1	h_2	Percent of Fatigue Life Used For Stress	For Strain At W.C.	At A.C.
11.8	4.0	14.31	56.66	90.64
10.0	10.0	27.01	58.35	100.58
9.0	13.0	47.72	61.46	101.29
8.0	19.0	85.23	37.09	50.93
7.8	27.0	85.51	10.74	11.54

the five different types of axles were of the order of an average of 5.3 percent in the strain zone and an average of 9.0 percent in the stress zone. These differences were considered as normal because according to Al-Arifi (3) "If the chosen thickness of asphaltic concrete is off by ± 0.1 in. the fatigue life used for the controlling criteria will be off from 100 percent by ± 6 percent, and if the chosen thickness of the granular base is off by ± 0.1 in., the fatigue life used by the controlling criteria will be off from 100 percent by ± 2 percent." This means that a better reading of the design charts, produces a better result.

EXAMPLE 2. Design for a four-lane, rural, interstate, highway at an elevation of 1000'. The design average number of vehicles was found to be 171 vpd. on the design lane. The design period is 20 years. The materials used for this pavement have the following modulus of elasticity:

E_1 = 200,000 psi, E_2 = 20,000 psi, and E_3 = 15000 psi

The expected number of vehicles in 20 years would be:

N = 171 x 20 x 365 = 1248300 vehicles

For this situation the equivalency factors for strain zone and stress zone were:

strain zone F_{fa} = 3.40, F_{ta} = 0.95 (from Table 12).

stress zone F_{fa} = 4.00, F_{ta} = 1.00 (from Table 13).

then,

$$\text{ESA for strain zone} = 1248300(0.10 \times 3.40 + 0.25 + 0.22 \times 2 \times 0.95)$$
$$= 1258286 \text{ repetitions } (1.26 \times 10^6).$$

$$\text{ESA for stress zone} = 1248300(0.10 \times 4.0 + 0.25 + 0.22 \times 2 \times 1.0)$$
$$= 1360647 \text{ repetitions } (1.36 \times 10^6).$$

An interpolation was required and performed as Example 1. The combinations of thicknesses chosen were (from Figure 7):

	Strain Zone		Stress Zone	
h_1	4.8	4.3	4.1	4.0
h_2	4.0	5.0	9.0	20.0

The output of the ASPDSN program gave the results shown in Table 17. The output of the ASPDSN program with the five different types of axles is shown in Table 18. This time, the differences were an average of 11 percent and 0.3 percent in the strain and stress zones respectively but optimum at h_1 = 4.3" and h_2 = 5.0" in both cases.

The values of h_1 and h_2 usually are rounded to the highest half of inch but in these cases it was not done because the points on the design charts were taken for the ASPDSN program as were read.

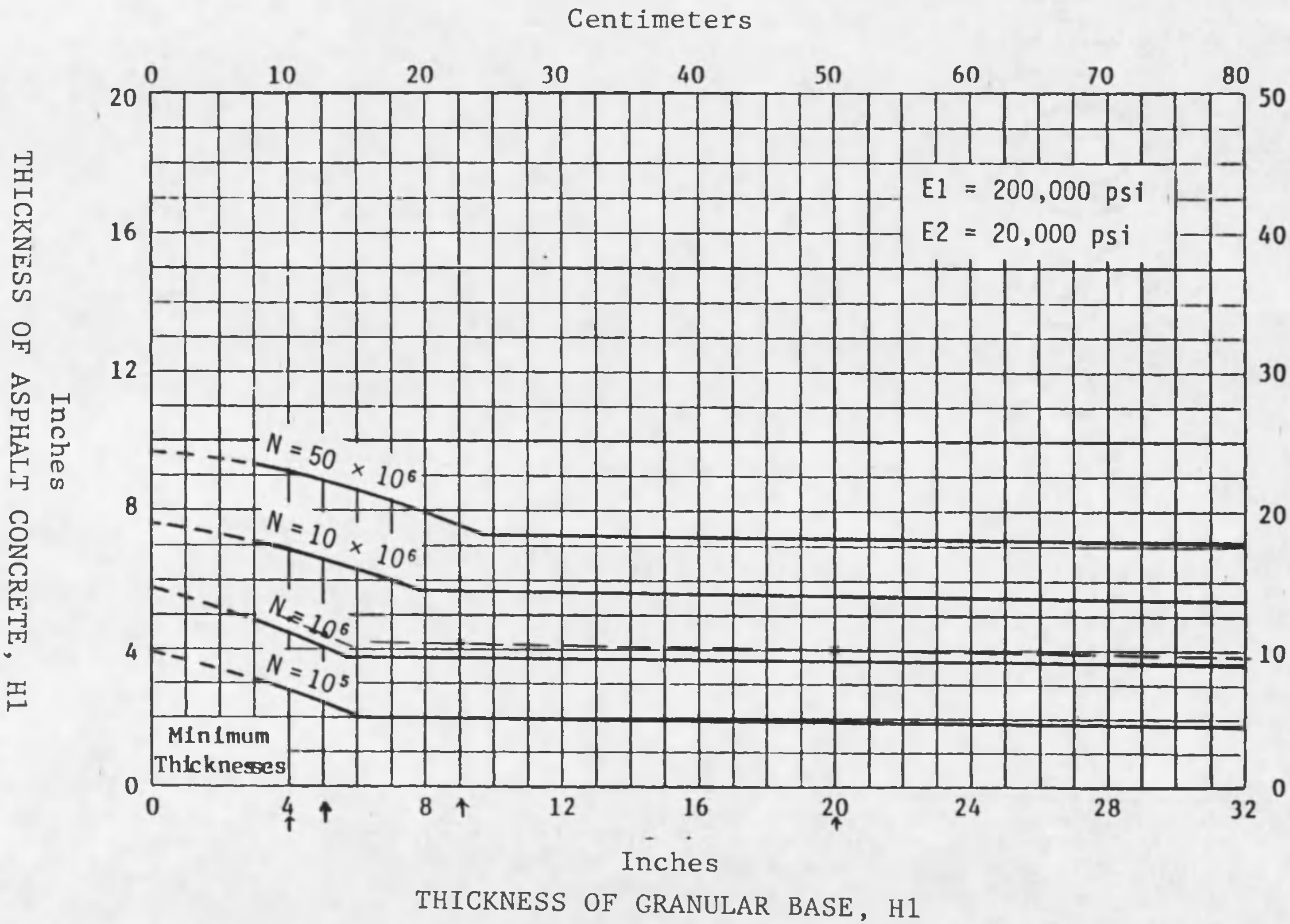

Figure 7. Design Curves for 16,000 Pound Single-Axle Load, Elevation = 1000 Feet Subgrade Modulus (E_3) = 15,000 PSI. -- After Al-Arifi

Table 17. Percents of Fatigue Life Used by SA at 1.36×10^6 Repetitions Using Different Combinations of h_1 and h_2

Thicknesses h_1	h_2	Percent of Fatigue Life Used For Stress	For Strain At W.C.	For Strain At A.C.
4.8	4.0	41.04	80.01	52.26
4.3	5.0	71.05	92.00	71.08
4.1	9.0	86.24	26.17	39.19
4.0	20.0	87.68	0.90	1.58

Table 18. Totals of Percents of Fatigue Life Used by the Five Different Axles Considered by Jimenez' Method

Thicknesses h_1	h_2	Percent of Fatigue Life Used For Stress	For Strain At W.C.	For Strain At A.C.
4.8	4.0	45.07	70.97	33.97
4.3	5.0	76.92	81.69	46.27
4.1	9.0	85.75	19.14	23.14
4.0	20.0	87.59	0.57	0.93

CHAPTER 6

CONCLUSIONS

Although Jimenez' design method belongs to a group which uses theoretical concepts for the design of a flexible pavement, the equivalancy factors were obtained in an empirical way. The author tried to find a relationship between the data obtained by the output of the ASPDSN program, the data given to the program, and the equivalancy factors without success. Such as Deacon (15) did it. Deacon gave the following expression for equivalency factors:

$$F_i = \left(\frac{\varepsilon_i}{\varepsilon_b}\right)^4$$

where

ε_i = maximum principal tensile strain at bottom of surface course for an $\underline{i}$ axle load.

ε_b = same as above but for an axle base of the system.

For this reason, the equivalency factors obtained belong to a group of empirical development.

The reader is reminded that the equivalency factors were developed and verified for a rural, interstate highway or similar in which the percents for front axle, single axle, and tandem axle would be 10, 25, and 22 respectively as was found by Jimenez' (2).

From the analysis of the equivalency factors some conclusions were obtained. These conclusions are:

1. Two different types of equivalency factors were obtained that correspond to the failure criteria. That is, the equivalency factors for the zone in which the failure of the pavement occurs due to the excess of repetition of strains or stresses.
2. Passenger car and pick-up truck have an insignificant effect in the pavement system and can be neglected.
3. The effect produced by tandem axle was more destructive than the effect produced by front axle in the strain zone. While, the opposite effect was observed in the stress zone.
4. The effect of elevation in the equivalency factors was very low. Small differences between equivalency factors for pavements with same characteristics of the components of the system but different elevation were found.
5. The effect of the number of repetitions was very significant. For this reason, three kinds of equivalency factors were developed for the strain

zone, and two for the stress zone for each design chart.

6. The modulers of elasticity of the subgrade had a significant effect in the equivalency factors. As noted in Table 12.
7. In comparison and contrast with other agencies or groups, the equivalency factors developed were found to correspond to well defined zones of failure.

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