Development of a Rational Thickness Design Method for Rigid Pavements

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A computer program, MEDCONP (Mechanistic Design of Concrete Pavement) was developed to design and evaluate jointed concrete pavements. This procedure uses a mechanistic approach and considers important factors (such as the thermal gradient in the concrete slab and the daily and hourly traffic load distribution) that have not been considered in the past. Other design factors considered include the slab length, elastic modulus, flexural strength of concrete, subgrade modulus, traffic growth rate, proportioning of traffic in multiple lanes, and design life. Fatigue theory and Miner's rule are used to determine required slab thickness for designing a new pavement and evaluating the structural adequacy of an existing pavement. A design example is also given in this paper to evaluate the suitability of the design procedure used in the MEDCONP program.

Concrete pavements in Florida have shown widely different performance. Some have performed extremely well and have served beyond their design service life. Some have shown severe signs of distress and failure prematurely. When considering the wide variation of the performance of concrete pavement and the fact that most of the pavements were designed in accordance with the AASHTO Design Guide (*1*), it becomes apparent that the design procedures must be reassessed.

In the two most widely used design procedures, AASHTO Design Guide and the Portland Cement Association (PCA) thickness design method (*2*), the effects of temperature variations in the pavement slab have not been taken into direct consideration. However, in reality, the temperature variations in a concrete slab can greatly affect the structural response of a pavement. During the day, the slab tends to curl up at the interior due to a positive temperature differential in the slab (the top of the slab is warmer than the bottom). During the night, the slab tends to curl up at the edges and joints due to a negative temperature differential.

When loads are applied to the slab during these curling conditions, the maximum stresses in the slab could be substantially higher than when the slab is fully supported by the subgrade. The damages to the slab caused by these critical thermal load-induced stresses could be much higher than those under full subgrade support conditions. Ignoring the effects of temperature variation on the response of concrete pavement could result in an underdesign of the pavement.

Because of the need to incorporate the effects of temperature variations in a pavement slab-in design, a computer program, MEDCONP (Mechanistic Design of Concrete Pavement), was developed. The program contains two parts, the program itself and a data base. The program can be used to design a jointed concrete pavement and to estimate the remaining service life of an existing pavement using a mechanistic approach. In addition to the design factors used in the conventional design procedures, such as the AASHTO guide and the PCA method, the effects of temperature variation on the concrete pavement response are also considered in this procedure. The program first calculates the maximum stress in the slab caused by each combination of thermal and load condition for a given set of pavement parameters. The fatigue theory and Miner's rule are then used to determine the number of applications of load to failure for each load level and to determine the total damage to the pavement. These results are then used to determine the required slab thickness for the design of a new pavement or the remaining service life of an existing pavement, using an interactive procedure.

The data base stores the theoretical maximum stresses caused by different thermal load conditions for different combinations of pavement parameters and is used by the MEDCONP program to compute the maximum thermal load-induced stresses in the slab for each given condition. The analytical results stored in the data base were computed by a finite-element computer program, FEACONS IV (*3*,*4*).

DEVELOPMENT OF THE DATA BASE

Modeling Concrete Pavement

The FEACONS (Finite Element Analysis of Concrete Slabs) program, Version IV, was developed at the University of Florida and used to compute the analytical results stored in the data base. A detailed description of the program can be found in Tia et al. (*3*,*4*). A brief description of the model used is given in this section.

A jointed concrete pavement is modeled as a three-slab system as shown in Figure 1. Because the analysis of the response of a concrete pavement generally involves the computation of deflection and stresses on a slab (which is affected mainly by its two adjacent slabs), it is usually adequate to model a concrete pavement as a three-slab system. A concrete slab is modeled as an assemblage of rectangular plate bending elements with three degrees of freedom at each node. Either a homogeneous slab or a composite slab consisting of two layers bonded together can be modeled.

The subgrade is modeled as a liquid or Winkler foundation, which is modeled by a series of vertical springs at the nodes. Load transfers across the joints between two adjoining slabs are modeled by shear (or linear) and torsional springs connecting the slabs at the nodes of the elements along the joint. Frictional effects at the edges are modeled by shear springs at the nodes along the edges.

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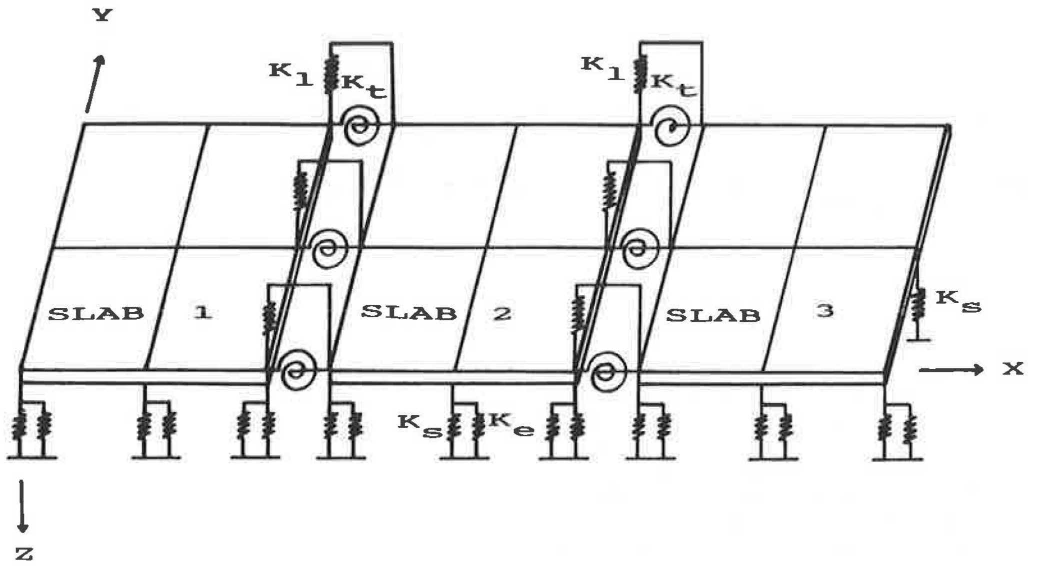

FIGURE 1 Finite element modeling of a three-slab pavement system.

When a temperature differential in the slab is considered, the temperature is assumed to vary linearly from the top to the bottom of the slab. The concrete is modeled as linearly elastic and isotropic.

The program uses an incremental computational procedure. The force vectors due to the weight of the slab, thermal gradients, and applied loads are applied in increments. At the end of each load increment, the stiffness matrix of the system is adjusted according to the new subgrade support condition (*3*,*4*).

MEDCONP Data Base

The theoretical maximum stresses in a concrete slab caused by the combinations of different single axle loads and temperature differentials of pavements with different dimensions and material properties were computed. The pavement parameters used to generate the data base include the slab length, slab thickness, subgrade stiffness, and concrete modulus of elasticity.

In the data base, the slab length varies from 12 ft (3.7 m) to 24 ft (7.3 m) and the slab thickness ranges from 6 in. (15.2 cm) to 13 in. (33.0 cm). The subgrade stiffness varies between 100 pci (27.2 MN/m^3) and 800 pci (217.2 MN/m^3) and the concrete modulus between 3,000 ksi (20.7 GPa) and 6,000 ksi (41.3 GPa). Fixed values of joint and edge stiffnesses are used in the data base. The temperature differential, which is equal to the temperature at the top of the slab, minus the temperature at the bottom of the slab varies from -20°F (-11.1°C) to $+30$°F ($+16.7$°C) in the data base.

Results of previous analyses (*5*) have indicated that the two most critical loading conditions in a pavement were (a) the combination of a positive or zero temperature differential in the slab with an axle load at the edge center and (b) the combination of a negative temperature differential in the slab with an axle load at the slab corner. These two loading conditions are used in computing the critical stresses that are stored in the data base.

To reduce the size of the data base, dual wheels are treated as a single wheel with the same total weight. Analysis results have indicated that, when dual wheels are modeled as a single wheel, the computed stress is only slightly higher. Thus, a slightly more conservative design will result from this approach.

The data in the data base are stored in three files: FI12.DBK, FI20.DBK, and FI24.DBK (according to the length of the concrete slab). For instance, the file FI20.DBK stores the data for concrete pavements with a slab length of 20 ft (6.1 m). Only the maximum stresses caused by single-axle loads are stored in this data base.

When a tandem-axle load is encountered, it is converted to a number of single-axle loads having the same wheel load that will produce the same damage to the pavement as that produced by the tandem-axle load. The method of converting a tandem-axle load to a number of single-axle loads will be presented later in this paper.

A constant slab width of 12 ft (3.7 m) was used in computing the maximum stresses. The concrete was assumed to have a constant coefficient of thermal expansion of 6×10^{-6}/°F (10.8×10^{-6}/°C).

DEVELOPMENT OF MEDCONP COMPUTER PROGRAM

Factors Considered in the Design Procedure

The MEDCONP program used a mechanistic approach. The factors considered in this design procedure included (a) length and thickness of concrete slabs, (b) elastic modulus and flexural strength of concrete, (c) stiffness of subgrade or the combination of subbase and subgrade, (d) daily and hourly traffic distribution, and (e) thermal gradient in the slab.

The maximum stress caused by each combination of thermal gradient and axle load for the pavement with a set of given pavement parameters and dimensions was first obtained from the data base. The ratio of computed maximum stress to flexural strength of concrete was then computed for all load cases. Finally, these ratios were used in conjunction with the fatigue theory and Miner's rule to check the adequacy of the pavement section design or to estimate the expected service life of the pavement.

Fatigue Theory and Miner's Rule

The number of cycles that will cause the concrete pavement slab to fail for each stress level is computed by means of the fatigue theory. The fatigue theory states that the number of load applications that a concrete slab can sustain depends on the ratio of applied tensile stress to the modulus of rupture of the concrete. In the MEDCONP program, it is assumed that the concrete can take an unlimited number of load repetitions if the stress-to-strength ratio is less than 0.5. When the ratio is greater than 0.5, the allowable load repetitions for the concrete can be determined from typical fatigue curves. Two typical fatigue curves are shown in Figure 2 (*6*). Of these two curves, the one developed by Bradbury is used in the MEDCONP program. It should be stressed that this fatigue curve is not necessarily the only curve that can be used. If desired, a different fatigue curve can be incorporated into the program by a slight modification of the program.

Once the number of load applications that the concrete slab can take for all load cases is determined, Miner's rule is used to check the adequacy of the pavement section design. According to Miner's rule, fatigue failure will occur when the sum of the ratio of number of load repetitions to number of load repetitions to cause failure for all stress levels is equal to or greater than one.

Traffic Distribution

To allow for the effects of temperature variation on the concrete pavement performance, each year can be divided into as many as twelve intervals (to account for seasonal temperature variation) and each day can be divided into 24 intervals (to account for daily temperature variation). The traffic distribution has to be obtained for each time increment in a day, for each seasonal interval. The information required includes (a) type of each axle load, whether single or tandem, (b) weight of each axle load, and (c) number of applications of each axle load. The traffic distribution required to be input to this program is that in one direction only. This enables the pavement lanes in opposite directions to be designed individually if they have different traffic distribution.

When the pavement has more than one lane in each direction, it is known that a larger portion of the traffic uses the right lane (*7*). The proportion of traffic in the right lane is both a function of the number of lanes in one direction and the average daily traffic (ADT) in one direction. This relationship, as shown in Figure 3, was derived by the PCA (*2*). From Figure 3, two equations are developed and listed as follows:

For two lanes in one direction,

$$\mathrm{TDF} = 1.5765 - 0.1922 \log_{10}(\mathrm{ADT}) \qquad (1)$$

For three lanes in one direction,

$$\mathrm{TDF} = 1.4500 - 0.1922 \log_{10}(\mathrm{ADT}) \qquad (2)$$

where TDF equals the proportion of traffic in the traffic lane, and ADT equals the average daily traffic in one direction.

It should be noted that the ADT in different seasonal intervals need not be the same.

Conversion of Tandem-Axle Loads

As mentioned earlier in this paper, only the stresses caused by single-axle loads were stored in the data base. To use the

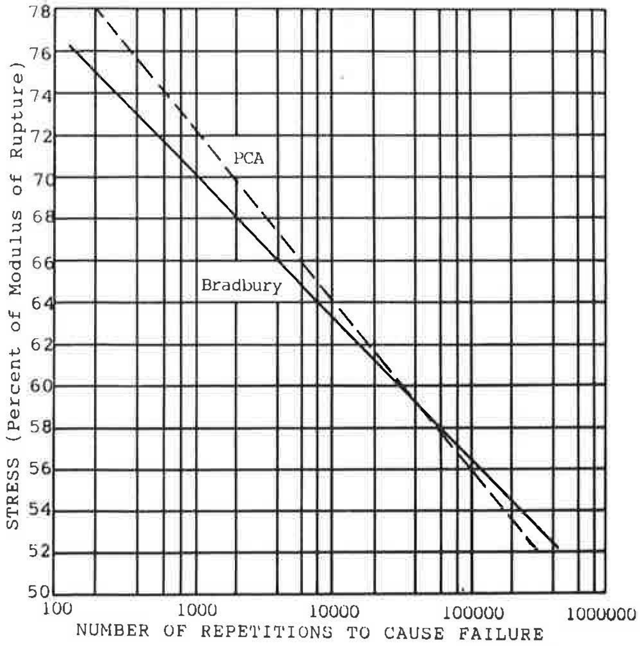

FIGURE 2 Fatigue curves for plain concrete (*6*).

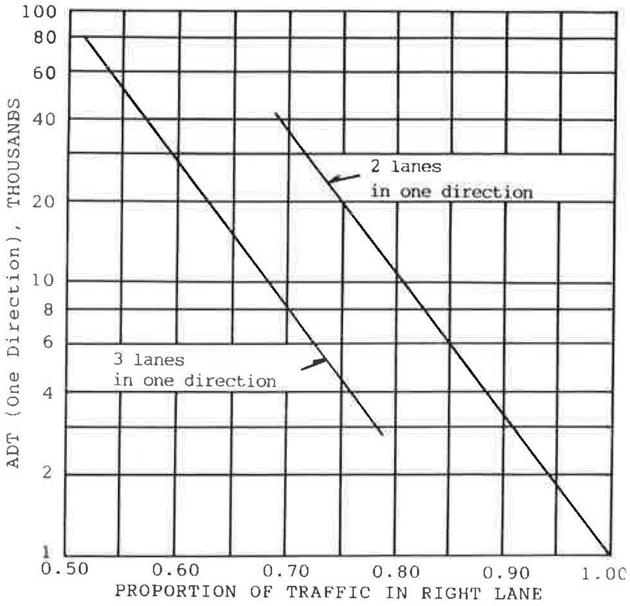

FIGURE 3 Proportion of traffic in the right lane of a multilane divided highway (*2*).

data base for tandem-axle loads, an effort was made to establish relationships between the maximum stresses caused by a tandem-axle load and those caused by a single-axle load with the same wheel loads and at the same temperature differentials. In the development of these relationships, a typical pavement with the following dimensions and parameters was used:

1. Slab length of 20 ft (6.1 m) and width of 12 ft (3.7 m),
2. Slab thickness of 9 in. (23 cm),
3. Concrete modulus of 4,000 ksi (27.6 GPa),
4. Subgrade modulus of 0.40 kci (108.6 MN/m^3),
5. Edge stiffness of 10 ksi (68.9 MPa),
6. Linear joint stiffness of 250 ksi (1.72 GPa), and
7. Torsional joint stiffness of 2000 k-in./in. (8.9 MN-m/m).

The maximum stresses caused by the combinations of various axle loads (either single-axle or tandem-axle) and various temperature differentials were computed using FEACONS IV. The temperature differential in the slab was varied from −20°F (−11.1°C) to +30°F (+16.7°C), and the magnitude of axle load ranged from zero to 30 kips (133.5 kN) for single-axle load and from zero to 60 kips (267 kN) for tandem-axle load. Again, the axle load was applied at the edge center for a positive temperature differential condition and at the slab corner for a negative temperature differential condition. For each temperature differential, the ratio of maximum stress caused by a tandem-axle load to that caused by a single-axle load with the same magnitude of wheel loads was calculated for each wheel load. The results of the analysis are shown in Table 1.

It should be noted that the wheel loads listed in the first column in Table 1 represent the weight of one wheel (or the total weight of dual wheels, if dual wheels were encountered). For instance, a wheel load of 5 kips (22.3 kN) represents either a single-axle load of 10 kips (44.5 kN) or a tandem-axle load of 20 kips (89 kN). As displayed in Table 1, the stress ratio varies with the change of both the wheel load and the temperature differential. For the condition of a negative temperature differential when the critical loading position is the corner load, the stress ratios are all greater than 1. For the condition of a positive or zero temperature differential when the critical loading position is the edge load, the stress ratios are all less than 1.

To establish the relationship between the maximum stress ratio and the combination of wheel load and temperature differential, a regression analysis was performed. It was found that the maximum stress ratio can be related to the wheel load and temperature differential by the following equations:

For the corner load condition,

$$\mathrm{COEFI} = 0.006494 \times \mathrm{WLOAD} + 0.000596 \times \mathrm{TEMDIF} + 1.014285 \qquad R^2 = 0.8159 \tag{3}$$

For the edge load condition,

$$\mathrm{COEFI} = -0.006531 \times \mathrm{WLOAD} + 0.003099 \times \mathrm{TEMDIF} + 0.92731 \qquad R^2 = 0.6662 \tag{4}$$

where

COEFI = maximum stress ratio,
WLOAD = magnitude of wheel load (in kips),
TEMDIF = temperature differential in the slab (in °F), and
R = coefficient of correlation.

Equations 3 and 4 were used in the MEDCONP program for this purpose. Because the edge load produces the highest stress when the pavement slab has a positive or zero temperature differential, Equation 4 is used for this condition. Similarly, Equation 3 is used when the pavement slab has a negative temperature differential.

The conversion of any tandem-axle load to a single-axle load involved the following steps:

1. Calculate the maximum stress ratio by using either Equation 3 or Equation 4 (depending on the temperature differential in the slab),
2. Divide the magnitude of the tandem-axle load by 2, and
3. Multiply the divided axle load by the maximum stress ratio.

One application of the tandem-axle load was then treated as two applications of a single-axle load with the magnitude as obtained when using these three steps.

It should be noted that the method of converting a tandem-axle load into an equivalent single-axle load (ESAL) generates only approximate stresses. The directly computed stresses caused by tandem-axle loads should be used to produce more accurate results.

A data bank for stresses caused by tandem-axle loads is currently being developed. Once this portion of the data base is complete, it will be incorporated into the program to replace the approximation method as presented above.

Program Structure and Algorithm

The flowchart of the MEDCONP program is shown in Figure 4. The program execution consists of the following major steps:

1. *Input data.* Data can be input either from a specified file or from the terminal. For the case of designing a new pavement, the required data are (a) intended design life, (b) annual growth rate of traffic, (c) number of lanes in one direction, (d) length and trial thickness of concrete slab with a fixed slab width of 12 ft, (e) elastic modulus and flexural strength of concrete, (f) subgrade modulus, (g) seasonal and daily variations of temperature differential in the slab, and (h) daily traffic distribution. The data required to evaluate an existing pavement are essentially the same as those listed above except that the intended design life is omitted and the slab thickness is known.
2. *Calculate proportion of traffic.* The traffic volume in the right lane must be determined. On a multilane divided highway, the proportion of traffic in the right lane is calculated using either Equation 1 or Equation 2.
3. *Compute maximum stresses.* The data files to be used for a particular case are determined according to the slab

TABLE 1 RATIO OF MAXIMUM STRESSES CAUSED BY TANDEM- AND SINGLE-AXLE LOADS ON CONCRETE SLABS WITH TEMPERATURE DIFFERENTIAL

WHEEL LOAD (kips)		TEMPERATURE DIFFERENTIAL (°F)						
		CORNER LOAD			EDGE LOAD			
		-20	-10	0	0	10	20	30
0	T-AXLE	310	155	9	9	160	285	379
	S-AXLE	310	155	9	9	160	285	379
	RATIO	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	T-AXLE	313	158	41	39	186	326	415
	S-AXLE	310	155	40	47	192	333	431
	RATIO	1.010	1.019	1.025	0.830	0.969	0.979	0.963
5	T-AXLE	320	166	92	98	239	395	492
	S-AXLE	311	156	88	118	246	400	509
	RATIO	1.029	1.064	1.046	0.830	0.972	0.988	0.967
7	T-AXLE	325	172	127	137	278	420	542
	S-AXLE	312	159	120	165	294	443	563
	RATIO	1.047	1.082	1.058	0.830	0.946	0.948	0.963
10	T-AXLE	334	185	182	196	335	472	609
	S-AXLE	314	164	169	236	365	503	640
	RATIO	1.064	1.128	1.077	0.831	0.918	0.938	0.952
13	T-AXLE	343	202	237	255	393	517	670
	S-AXLE	318	179	217	307	437	573	716
	RATIO	1.079	1.129	1.092	0.831	0.899	0.902	0.936
15	T-AXLE	348	215	274	294	432	559	688
	S-AXLE	321	192	249	355	485	623	762
	RATIO	1.084	1.120	1.100	0.828	0.891	0.897	0.903

NOTE: T-AXLE = Tandem-Axle Load S-AXLE = Single-Axle Load

RATIO = Stress caused by Tandem-Axle Load/Stress caused by Single-Axle Load

length of the pavement. The maximum stress caused by each combination of temperature differential and axle load for a given set of pavement parameters is obtained by extracting the appropriate data from the data bank and interpolation. This is done by the subroutine INTEP.

4. *Determine allowable repetitions for each stress level.* Subroutine CALCUL performs three tasks. First, it calculates the maximum stress by interpolation between slab lengths. Second, it determines the allowable repetitions for each stress level. The ratio of expected applications to the allowable repetitions is then computed for each stress level. Finally, the sum of all of the ratios is computed.
5. *Use Miner's rule.* The expected service life of an existing pavement or the design thickness of the concrete slab of a new pavement is determined using Miner's rule.

EVALUATION OF MEDCONP

To evaluate the suitability of the design procedure for rigid pavement used in MEDCONP, the program was applied to a design example. In this example, the required thickness of a four-lane, interstate highway pavement located in a rural area is to be determined using both the new AASHTO Design Guide and MEDCONP. The same set of design data was used in both methods.

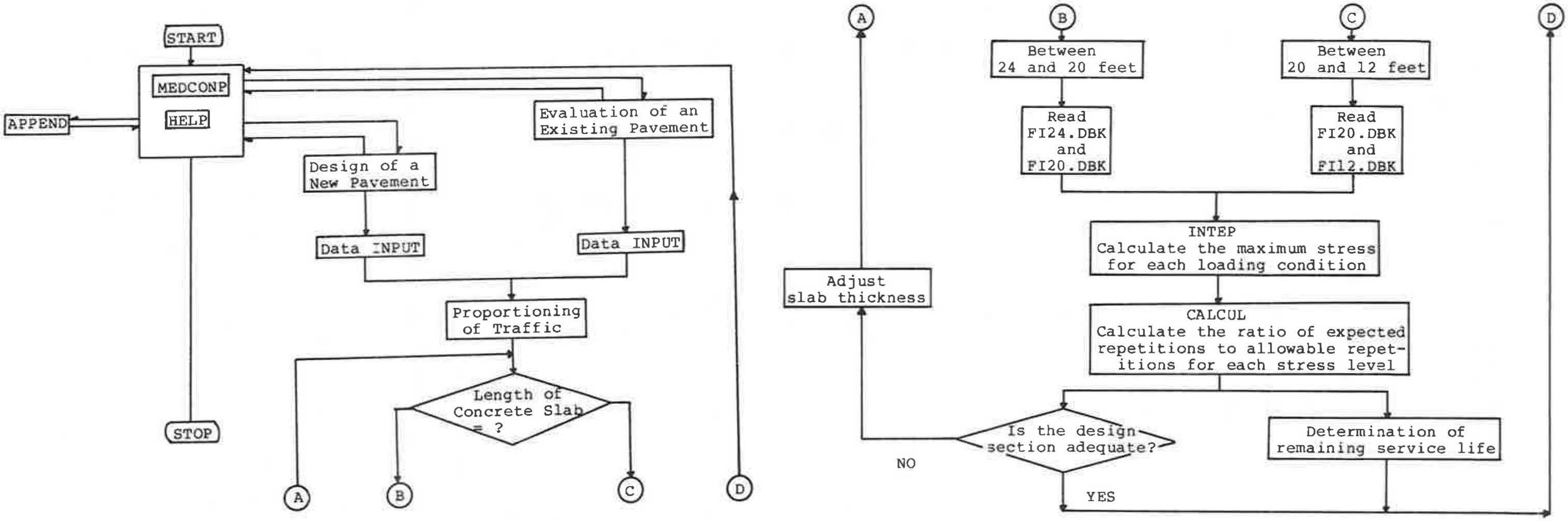

FIGURE 4 MEDCONP flowchart.

Two types of analyses will be performed using MEDCONP. The first accounts for temperature variation, while the second assumes no temperature differential in the slab throughout the design period. The slab thicknesses determined using the AASHTO Design Guide and those obtained using MEDCONP (with and without the consideration of the temperature variations) are compared to evaluate the suitability of the use of MEDCONP in designing rigid pavements. The general design data used in this example are listed below:

1. Current ADT in one direction = 6028,
2. E_c = 3500 ksi (24.1 GPa), typical concrete modulus for Florida concrete pavements,
3. K_s = 0.20 kci (54 MN/m^3), typical modulus of subgrade reaction for conventional stabilized subbase,
4. σ_c = 700 psi (4.8 MPa), modulus of rupture for typical Florida concrete,
5. Annual growth rate (AGR) of traffic = 3 percent,
6. Doweled joints and tied concrete shoulders, and
7. Slab length of 16 ft (4.9 m) and slab width of 12 ft (3.7 m).

Determining Slab Thickness Using AASHTO Design Guide

Design Parameters

In addition to the design data listed above, the following design parameters are also needed to use the AASHTO Design Guide.

1. ΔPSI = 4.2 − 2.5 = 1.7, design serviceability loss, equals initial serviceability index (P_0) minus terminal serviceability index (P_t),
2. J = 2.7, very good load transfer between two adjoining slabs,
3. C_d = 1.0, good drainage condition,
4. R = 95 percent, reliability factor, as suggested for interstate highways,
5. S_0 = 0.30, overall standard deviation, value obtained for rigid pavements on AASHO Road Test, and
6. ADT distribution, as listed in Table 2 (*1*).

Determining the Total 18-kip ESALs

Tables 3 and 4 show the traffic equivalence factors for rigid pavements for various single-axle and tandem-axle loads, respectively (*1*). From these two tables, the number of 18-kip (80 kN) ESALs for the first year was determined to be 2,610.2 for a trial slab thickness of 10 in. (25.4 cm). The computation of number of ESALs is shown in Table 5. The portion of traffic traveling in the design lane (right lane) is then determined using Equation 1. For a current ADT of 6,028 and a 3-percent annual traffic growth rate, the average ADT over the design period is calculated to be 7,746. Thus, from Equation 1, 83 percent of the total traffic will be driving on the design lane. The number of 18-kip (80-kN) ESALs on the design lane in the first year is obtained by multiplying 0.83 by 2,610.2 and is equal to 2163.9. With a 3-percent increase in traffic each year, the number of 18-kip (80-kN) ESALs in the last year of the design period (20th year) is 3,397.3 (2,163.9 × 0.03 × 19 + 2,163.9). Finally, the number of total 18-kip (80-kN) ESALs over the design period is calculated as follows:

Total 18-kip (80-kN) ESALs

$$= \frac{2163.9 + 3397.3}{2} \times 365 \times 20 = 20.3 \text{ million (approx.).}$$

Determining Slab Thickness

Design nomographs in the AASHTO Design Guide (as shown in Figures 5 and 6) are used to determine the required slab thickness. By connecting lines between specified design parameters, the required slab thickness is determined to be 9.5 inches (24.1 cm).

Determining Slab Thickness Using MEDCONP

Case A: Temperature Variation Considered

Hourly Traffic Distribution. According to the data on temperature differential in the slab obtained from the Gainesville Test Road located in the Bureau of Materials and Research, Florida Department of Transportation (*8*), it is determined to separate each year into four groups. Group 1 comprised December, January, and February; Group 2 comprised March, April, and May; Group 3 included June, July, and August; and Group 4 was September, October, and November. Data obtained from January 27 to 28, April 7 to 8, June 7 to 8, 1986, and October 7 to 8, 1985, are used to represent the typical variations of temperature differential in the slab for Groups 1 through 4, respectively.

Within each group, each day is further subdivided into several time increments. The time increments are selected such that the slab will be subjected to similar temperature differential in each increment. The number of time increments in each group may differ.

Finally, the number and type of traffic loads are assigned to each group and time increment with the basic assumption that most of the heavy trucks travel on the road during the early morning and passenger cars travel during the daytime. A sample traffic distribution by hour of the day and gross weight obtained at a weigh-in-motion station located south of Gainesville, Florida, on I-75 (*8*) are also used as guidelines. The axle load distribution in each group and time increment are listed in Tables 6 through 9.

Determination of Slab Thickness. After performing the analysis using the design data and MEDCONP, the slab thickness was determined to be 12.0 inches (30.5 cm).

Case B: Temperature Variation Not Considered

Because temperature differential in the slab is not considered in this case, it is not necessary to divide a year or a day into time increments. Only one group in the entire year and one time increment in each day are used. A temperature differential of zero is used. Therefore, the slab thickness is deter-

TABLE 2 AVERAGE DAILY TRAFFIC DISTRIBUTION (*1*)

Axle Load Groups (lbs)	Representative Axle Load (lbs)	No. of Axles
Single Axle		
Under 3000	2000	512
3000-6999	5000	536
7000-7999	7500	239
8000-11999	10000	1453
12000-15999	14000	279
16000-18000	17000	106
18001-20000	19000	43
20001-21999	21000	4
22000-23999	23000	3
Tandem Axle		
Under 6000	4000	9
6000-11999	9000	337
12000-17999	15000	396
18000-23999	21000	457
24000-29999	27000	815
30000-32000	31000	342
32001-33999	33000	243
34000-35999	35000	173
36000-37999	37000	71
38000-39999	39000	9
40000-41999	41000	0
42000-43999	43000	1
	ADT =	6028

mined (using the same design data as in the previous cases) to be 7.5 inches (19.1 cm).

SUMMARY

MEDCONP was developed to design and evaluate jointed concrete pavements. It uses a mechanistic approach and considers such important factors as the thermal gradient in the concrete slab and the daily and hourly traffic load distribution, which have not been considered in the past. The other design factors considered include the slab length, elastic modulus and flexural strength of concrete, subgrade modulus, traffic growth rate, proportioning of traffic in multiple lanes, and design life. For each applied load considered, the critical-induced stress in the slab is computed by assuming that the load is applied at the most critical loading position for the given thermal condition. These critical stresses are then used to evaluate the structural adequacy of the given pavement by means of the fatigue theory and Miner's rule.

As illustrated in the design example, temperature differential in the concrete slab greatly affects the required slab thickness. With the assumption of no temperature variation in the slab, the required slab thickness (as determined by MEDCONP) is 7.5 inches (19.1 cm). When the temperature variation is considered, the required slab thickness increases

TABLE 3 TRAFFIC EQUIVALENCE FACTORS FOR SINGLE-AXLE LOAD (*1*)

Axle Load		Slab Thickness (inches)						
Kips	kN	6	7	8	9	10	11	12
2	8.9	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	17.8	0.003	0.002	0.002	0.002	0.002	0.002	0.002
6	26.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8	35.6	0.04	0.04	0.03	0.03	0.03	0.03	0.03
10	44.5	0.10	0.09	0.08	0.08	0.08	0.08	0.08
12	53.4	0.20	0.19	0.18	0.18	0.18	0.17	0.17
14	62.3	0.38	0.36	0.35	0.34	0.34	0.34	0.34
16	71.2	0.63	0.62	0.61	0.60	0.60	0.60	0.60
18	80.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	89.0	1.51	1.52	1.55	1.57	1.58	1.58	1.59
22	97.9	2.21	2.20	2.28	2.34	2.38	2.40	2.41
24	106.8	3.16	3.10	3.23	3.36	3.45	3.50	3.53
26	115.7	4.41	4.26	4.42	4.67	4.85	4.95	5.01
28	124.6	6.05	5.76	5.92	6.29	6.61	6.81	6.92
30	133.4	8.16	7.67	7.79	8.28	8.79	9.14	9.34
32	142.3	10.81	10.06	10.10	10.70	11.43	11.99	12.35
34	151.2	14.12	13.04	12.34	13.62	14.59	15.43	16.01
36	160.1	18.20	16.69	16.41	17.12	18.33	19.52	20.39
38	169.0	23.15	21.14	20.61	21.31	22.74	24.31	25.58
40	177.9	29.11	26.49	25.65	26.29	27.91	29.90	31.64

NOTE: $P_t = 2.5$

TABLE 4 TRAFFIC EQUIVALENCE FACTORS FOR TANDEM-AXLE LOAD (*1*)

Axle Load		Slab Thickness (inches)						
Kips	kN	6	7	8	9	10	11	12
10	44.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	53.4	0.03	0.03	0.03	0.03	0.03	0.03	0.03
14	62.3	0.06	0.05	0.05	0.05	0.05	0.05	0.05
16	71.2	0.10	0.09	0.08	0.08	0.08	0.08	0.08
18	80.1	0.16	0.14	0.14	0.13	0.13	0.13	0.13
20	89.0	0.23	0.22	0.21	0.21	0.20	0.20	0.20
22	97.9	0.34	0.32	0.31	0.31	0.30	0.30	0.30
24	106.8	0.48	0.46	0.45	0.44	0.44	0.44	0.44
26	115.7	0.64	0.64	0.63	0.62	0.62	0.62	0.62
28	124.6	0.85	0.85	0.85	0.85	0.85	0.85	0.85
30	133.4	1.11	1.12	1.13	1.14	1.14	1.14	1.14
32	142.3	1.43	1.44	1.47	1.49	1.50	1.51	1.51
34	151.2	1.82	1.82	1.87	1.92	1.95	1.96	1.97
36	160.1	2.29	2.27	2.35	2.43	2.48	2.51	2.52
38	169.0	2.85	2.80	2.91	3.04	3.12	3.16	3.18
40	177.9	3.52	3.42	3.55	3.74	3.87	3.94	3.98
42	186.8	4.32	4.16	4.30	4.55	4.74	4.86	4.91
44	195.7	5.26	5.01	5.16	5.48	5.75	5.92	6.01
46	204.6	6.36	6.01	6.14	6.53	6.90	7.14	7.28
48	213.5	7.64	7.16	7.27	7.73	8.21	8.55	8.75

NOTE: $P_t = 2.5$

TABLE 5 COMPUTATION OF NUMBER OF 18-KIP ESALs

Axle Load (kips)	Equiv. Factor	No. of Axles	Equiv. 18-kip Single Axles
Single Axles			
2	0.0002	512	0.1024
5	0.006	536	3.216
7.5	0.025	239	5.975
10	0.08	1453	116.24
14	0.34	279	94.86
17	0.80	106	84.8
19	1.29	43	55.47
21	1.98	4	7.92
23	2.915	3	8.745
Tandem Axles			
9	0.01	337	3.37
15	0.065	396	25.74
21	0.25	457	114.25
27	0.735	815	599.025
31	1.32	342	451.44
33	1.73	243	420.39
35	2.215	173	383.195
37	2.8	71	198.8
39	3.495	9	31.455
43	5.245	1	5.245
		Total ESALs =	2610.2

to 12 inches (30.5 cm). For this thermal condition, the required slab thickness is higher than that determined by the AASHTO procedure.

For a region where the temperature differential in the concrete slab is small, it is expected that the MEDCONP procedure will produce a lower slab thickness than the AASHTO procedure. For a region where the temperature differential is high, the MEDCONP procedure will produce a higher slab thickness.

In summary, it is evident that temperature variation plays a major role in affecting the performance of concrete pavement and should be incorporated in the design procedure. MEDCONP takes this factor into account in the design procedure and has been demonstrated to run properly for its intended purposes. It should be noted that because MEDCONP assumes that the loads are applied at the critical positions on the slab, it should produce designs that are on the safe side.

FURTHER DEVELOPMENT OF MEDCONP

As a result of the large amount of time required to generate the data base in the program, the data base is still being expanded at this stage of development of the program. Further development of MEDCONP is now in progress and includes the following:

1. The data base will be expanded to account for the effects of joint and edge stiffness.

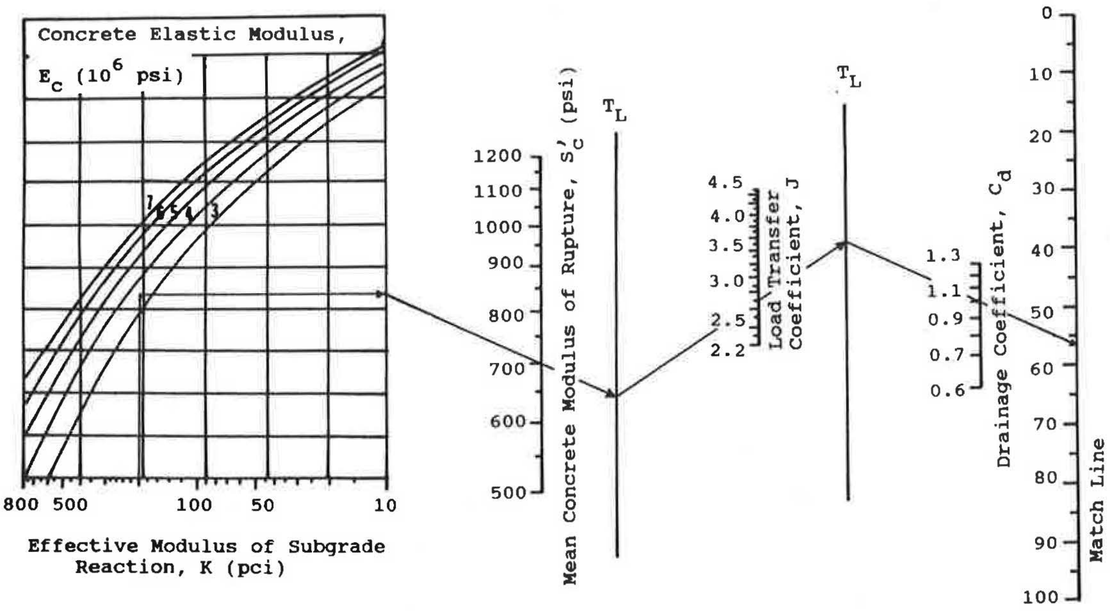

FIGURE 5 Determination of slab thickness using AASHTO method (Part 1) (*1*).

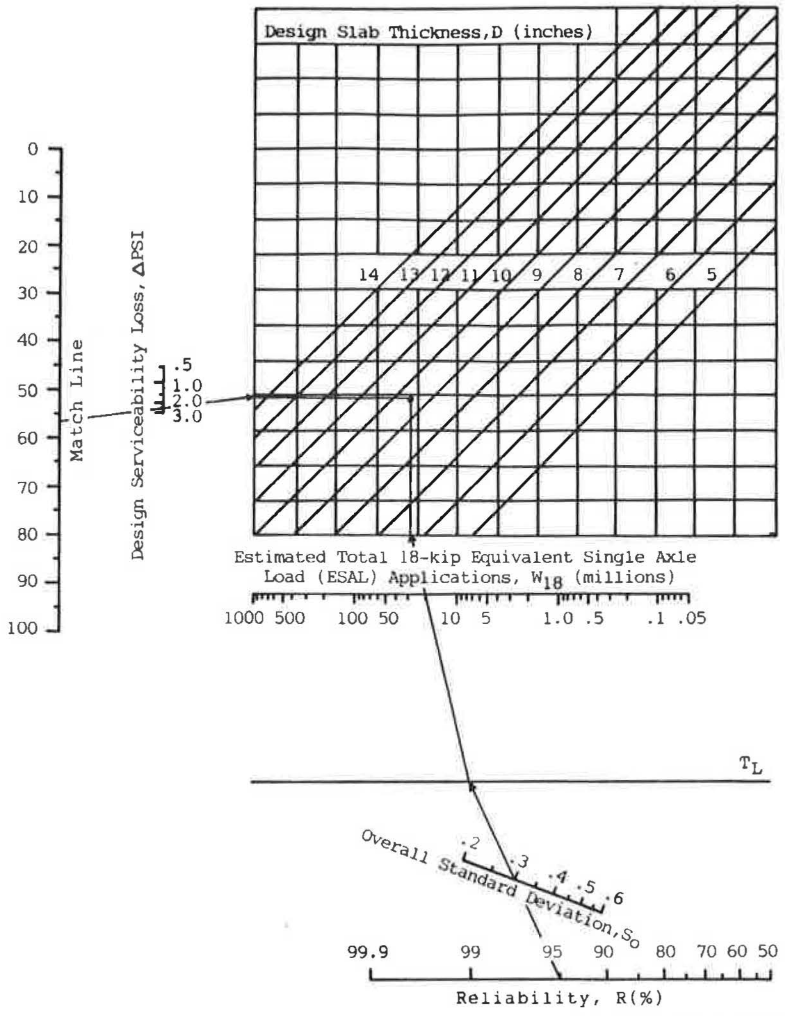

FIGURE 6 Determination of slab thickness using AASHTO method (Part 2) (*1*).

TABLE 6 CURRENT HOURLY TRAFFIC DISTRIBUTION FOR GROUP 1

Time Increment	ΔT	Single-Axle Load									Tandem-Axle Load										
		2	5	7.5	10	14	17	19	21	23	4	9	15	21	27	31	33	35	37	39	43
08-09	- 5.5	30	31	14	56	11	4	1	0	0	2	31	16	19	15	24	17	12	3	0	0
09-10	- 2.8	39	40	18	75	14	6	1	0	0	3	20	21	25	52	8	6	4	2	1	0
10-11	+ 0.8	26	28	12	65	15	5	1	0	0	0	13	22	27	15	8	6	4	3	1	0
11-12	+ 4.8	17	18	8	84	17	7	1	0	0	0	13	22	27	15	8	6	4	3	1	0
12-14	+ 7.3	32	34	15	140	25	8	4	0	0	0	20	38	44	32	17	12	9	4	0	0
14-15	+ 0.9	17	18	8	61	11	4	0	0	0	0	9	17	22	23	2	1	0	0	0	0
15-16	- 5.4	21	22	10	70	14	5	1	0	0	0	8	19	22	38	11	8	6	3	0	0
16-18	- 8.5	60	62	28	136	25	8	3	0	0	2	35	38	44	38	24	17	13	2	0	0
18-20	-11.0	77	81	36	136	31	8	3	0	0	1	61	37	44	90	33	23	17	7	0	0
20-04	-12.2	128	134	60	444	82	32	18	4	3	1	58	119	134	299	135	96	67	32	6	1
04-08	-11.5	65	68	30	186	34	19	10	0	0	0	69	52	57	198	69	49	35	14	1	0

TABLE 7 CURRENT HOURLY TRAFFIC DISTRIBUTION FOR GROUP 2

Time Increment	ΔT	Single-Axle Load									Tandem-Axle Load										
		2	5	7.5	10	14	17	19	21	23	4	9	15	21	27	31	33	35	37	39	43
00-04	- 9.2	56	58	26	233	45	17	11	3	1	1	23	63	70	140	73	52	37	14	4	1
04-07	-10.7	37	39	17	135	23	16	8	0	0	0	34	38	41	175	56	40	28	10	0	0
07-08	- 7.9	28	29	13	51	11	3	2	0	0	0	35	14	16	23	13	9	7	4	1	0
08-09	- 2.1	30	31	14	56	11	4	1	0	0	2	31	16	19	15	24	17	12	3	0	0
09-10	5.5	39	40	18	75	14	6	1	0	0	3	20	21	25	52	8	6	4	2	1	0
10-11	12.0	26	28	12	65	15	5	1	0	0	0	13	17	19	15	11	8	6	1	0	0
11-12	17.2	17	18	8	84	17	7	1	0	0	0	13	22	27	15	8	6	4	3	1	0
12-15	21.0	49	52	23	201	36	12	4	0	0	0	29	55	66	55	19	13	9	4	0	0
15-16	17.3	21	22	10	70	14	5	1	0	0	0	8	19	22	38	11	8	6	3	0	0
16-17	9.3	21	22	10	61	11	3	2	0	0	1	16	17	19	15	13	9	7	2	0	0
17-18	5.7	39	40	18	75	14	5	1	0	0	1	19	21	25	23	11	8	6	0	0	0
18-19	- 0.8	41	43	19	61	11	5	1	0	0	0	32	16	19	52	13	9	7	2	0	0
19-20	- 3.8	36	38	17	75	20	3	2	0	0	1	29	21	25	38	20	14	10	5	0	0
20-22	- 5.9	50	52	23	112	21	6	5	0	0	0	23	31	33	84	39	28	20	8	0	0
22-00	- 7.5	22	24	11	99	16	9	2	1	2	0	12	25	31	75	23	16	10	10	2	0

TABLE 8 CURRENT HOURLY TRAFFIC DISTRIBUTION FOR GROUP 3

Time Incre-ment		Single-Axle Load									Tandem-Axle Load										
	ΔT	2	5	7.5	10	14	17	19	21	23	4	9	15	21	27	31	33	35	37	39	43
00-03	- 4.7	43	45	20	158	31	13	7	2	1	1	20	44	48	125	45	32	23	13	3	1
03-06	- 5.3	39	41	18	173	30	15	9	1	0	0	25	47	52	143	60	43	30	8	1	0
06-07	- 3.0	11	11	5	37	7	5	3	0	0	0	12	10	11	47	24	17	12	3	0	0
07-08	2.0	28	29	13	51	11	3	2	0	0	0	35	14	16	23	13	9	7	4	1	0
08-09	8.1	30	31	14	56	11	4	1	0	0	2	31	16	19	15	24	17	12	3	0	0
09-10	13.5	39	40	18	75	14	6	1	0	0	3	20	21	25	52	8	6	4	2	1	0
10-12	18.5	43	46	20	149	32	12	2	0	0	0	26	39	46	30	19	14	10	4	1	0
12-14	22.7	32	34	15	140	25	8	4	0	0	0	20	38	44	32	17	12	9	4	0	0
14-15	21.1	17	18	8	61	11	4	0	0	0	0	9	17	22	23	2	1	0	0	0	0
15-17	14.2	42	44	20	131	25	8	3	0	0	1	24	36	41	53	24	17	13	5	0	0
17-28	8.5	39	40	18	75	14	5	1	0	0	1	19	21	25	23	11	8	6	0	0	0
18-19	3.0	41	43	19	61	11	5	1	0	0	0	32	16	19	52	13	9	7	2	0	0
10-21	- 1.7	60	63	28	140	32	5	5	0	0	1	42	38	44	61	44	31	22	8	0	0
21-00	- 4.8	48	51	23	146	25	13	4	1	2	0	22	39	45	136	38	27	18	15	2	0

TABLE 9 CURRENT HOURLY TRAFFIC DISTRIBUTION FOR GROUP 4

Time Incre-ment		Single-Axle Load									Tandem-Axle Load										
	ΔT	2	5	7.5	10	14	17	19	21	23	4	9	15	21	27	31	33	35	37	39	43
00-08	- 8.3	121	126	56	419	79	36	21	3	1	1	92	115	127	338	142	101	72	28	5	1
08-09	- 7.0	30	31	14	56	11	4	1	0	0	2	31	16	19	15	24	17	12	3	0	0
09-10	- 2.5	39	40	18	75	14	6	1	0	0	3	20	21	25	52	8	6	4	2	1	0
10-11	4.3	26	28	12	65	15	5	1	0	0	0	13	17	19	15	11	8	6	1	0	0
11-12	10.8	17	18	8	84	17	7	1	0	0	0	13	22	27	15	8	6	4	3	1	0
12-13	14.5	15	16	7	75	14	5	2	0	0	0	11	21	25	23	13	9	7	3	0	0
13-14	17.2	17	18	8	65	11	3	2	0	0	0	9	17	19	9	4	3	2	1	0	0
14-15	16.6	17	18	8	61	11	4	0	0	0	0	9	17	22	23	2	1	0	0	0	0
15-16	13.4	21	22	10	70	14	5	1	0	0	0	8	19	22	38	11	8	6	3	0	0
16-17	10.3	21	22	10	61	11	3	2	0	0	1	16	17	19	15	13	9	7	2	0	0
17-18	4.4	39	40	18	75	14	5	1	0	0	1	19	21	25	23	11	8	6	0	0	0
18-19	0.4	41	43	19	61	11	5	1	0	0	0	32	16	19	52	13	9	7	2	0	0
19-21	- 4.5	60	63	28	140	32	5	5	0	0	1	42	38	44	61	44	31	22	8	0	0
21-00	- 7.2	48	51	23	146	25	13	4	1	2	0	22	39	45	136	38	27	18	15	2	0

2. The data base will be expanded to include computed stresses caused by tandem-axle loads. When this portion of the data base is complete, using an equivalency factor to convert tandem-axle loads to single-axle loads will no longer be necessary.
3. The current data base contains data for only three slab lengths (12, 20, and 24 ft). To improve the accuracy of the program results, data for other slab lengths will also be incorporated.

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