National Examinations – December 2018

16-Civ-A6, Highway Design, Construction, and Maintenance

3 Hour Duration

NOTES

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper a clear statement of any assumptions made.

2. Any data, not given but required, can be assumed.

3. This is a **"CLOSED BOOK"** examination. Candidates may use one of two calculators, the Casio or Sharp approved models.

4. This exam includes five questions but only a total of **four** solutions is required. Only the first **four** solutions, as they appear in your answer book, will be marked.

5. All questions are of equal value (25% each). The marks for sub-questions are indicated in brackets when applicable.

6. For non-numerical questions, clarity and organization of the answer are important.

7. A ten page appendix is attached for reference.

Question 1:

The pavement for a 6-lane freeway located in an urban area is to be designed using AASHTO 93 Method. The design life of the pavement is 30 years and the projected Design ESAL is 12,000,000.

The following information is also available:

- The effective resilient modulus of the subgrade M_R = 10,000 psi.
- The subbase layer is an untreated silty sand with a resilient modulus (E_{SB}) of 22,000 psi.
- The base layer is an untreated granular material with a resilient modulus (E_B) of 30,000 psi.
- The elastic modulus of the asphalt concrete at 20°C (E_{AC}) is 450,000 psi.
- The quality of drainage is assumed to be good.
- The highway is in a busy area and traffic detours are difficult and expensive. The subgrade soil and the building materials used in the project were tested in the laboratory and the traffic information is accurate.
- The use of modern pavers allows the achieving of high level of initial serviceability values after the construction (p_0 = 4.5) and the lowest acceptable value of the serviceability index is p_t = 2.5.

Based on the provided information, determine the thicknesses of the different structural layers of the pavement using the AASHTO 93 Flexible Pavement Design Method. Assume reasonably any missing information and justify your assumptions.

Question 2:

A 2 km curved section of an urban expressway in an urban area is characterized by a radius of 600 m (to the centreline of the road). According to the MTO study on provincial highway volumes in 2010, the estimated AADT of this section is 45,200 vehicles/day. The highway is a four-lane divided highway with a posted speed of 100 km/h and a lane width of 3.75m. This section is mainly in a cut area with a slope of 3:1 in the clear zone.

a) [10 marks] Would you consider that this curve is safe (The radius is sufficient)?
b) [5 marks] What should be the recommended clear zone distance for this section of the highway?
c) [10 marks] What length of the spiral curve between the tangent sections and the circular curve would you recommend? (For the calculation of the spiral length, consider a relative slope of 0.004 at 120 km/h)

Question 3:

A Plain Jointed Concrete Pavement has been designed using the AASHTO 93 Pavement Design Method. The slabs are connected longitudinally and transversally using dowel and tie bars and asphalt shoulders were used. At the time of the design, limited geotechnical information was available and the designer assumed that the subgrade was infinite in thickness.

The following information and design assumptions were used for the preliminary design:

- Concrete slab: E_c = 4×106, S'_c = 700 psi
- Unbound Granular Subbase: D_{SB} = 12 in., E_{SB} = 30,000 psi.

- Resilient Modulus of the Subgrade: M_R = 5,000 psi.
- Terminal Serviceability index value: p_t = 2.5
- Reliability and Standard Deviation: R = 95% and S_0 = 0.35
- The quality of the drainage is good and the pavement is exposed to moisture level approaching saturation for 15% of the time.

Based on these assumptions and information, the design yielded a Concrete Slab thickness of 9 inches. However, the geotechnical team has conducted some boreholes in the jobsite and determined that a rigid layer was found at an average depth of approximately two feet.

a) [10 marks] Find the ESAL value that has been used in the original design.
b) [15 marks] What should be the new thickness of the concrete slab based on this new information?

Assume reasonably any missing information and justify your assumptions.

Question 4:

A vehicle was traveling at 90 km/h on a parabolic crest vertical curve section on a rural highway. A stalled vehicle was spotted on the same curve section and the drive immediately acted to stop the vehicle. Unfortunately, the driver struck the stalled vehicle at a speed of 10 km/h. An after-accident investigation reveals that the curve connects a +2% grade to the -3% grade, and has a length of 300 m. The design speed of this highway is 80km/h. The vehicle has an eye height of 1.38 m and the stalled vehicle has a height of 1.10 m. A series of test runs show that the coefficient of friction is 0.32. The driver later claimed that there was not enough sight distance available at this section.

a) [17 marks] Would you agree with the driver's claim and why?
b) [8 marks] What could be the other potential factors that had contributed to the accident?

Question 5:

The first year AADT on a 4-lane freeway located in a new urban area is expected to be 17,500 veh/day and the projected vehicle mix during the first year is as follows:

- Passenger cars = 78%
- Single-unit trucks, two-axle, four-tire = 12%
- Single-unit trucks, two-axle, six-tire = 7%
- Single-unit trucks, six-axle or more = 3%

The growth rates for the different categories of vehicles are different and would change over the service life of the pavement. The projected growth rate for passenger cars is 2% per annum over the first 2 years but would increase to 6% per annum for the remaining life of the pavement. For the two-axle, 4-tire, single unit trucks, the growth rate is expected to be 3% per annum during the five years of the pavement life and will increase to 4% per annum for the remaining life of the pavement. The growth rate for all other categories of vehicles is expected to be 3% per annum throughout the life of the pavement. The design life of the pavement is 25 years.

Determine the design ESAL that should be used for the design of this pavement.

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APPENDIX

AASTO Flexible Pavement Design

TABLE IV-5 DISTRIBUTION OF TRUCK FACTORS (TF) FOR DIFFERENT CLASSES OF HIGHWAYS AND VEHICLES—UNITED STATES*

Vehicle Type	Truck Factors: Rural Systems: INTER-STATE	OTHER PRINCIPAL	MINOR ARTERIAL	COLLECTORS: MAJOR	COLLECTORS: MINOR	RANGE	Urban Systems: INTER-STATE	OTHER FREEWAYS	OTHER PRINCIPAL	MINOR ARTERIAL	COLLEC TORS	RANGE
Single-unit trucks												
2-axle, 4-tire	0.003	0.003	0.003	0.017	0.003	0.003-0.017***	0.002	0.015	0.002	0.006	...	0.006-0.015***
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19-0.41	0.17	0.13	0.24	0.23	0.13	0.13-0.24
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45-1.26	0.61	0.74	1.02	0.76	0.72	0.61-1.02
All single-units	0.06	0.08	0.08	0.12	0.03	0.03-0.12	0.05	0.06	0.09	0.04	0.16	0.04-0.16***
Tractor semi-trailers												
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37-0.91	0.98	0.48	0.71	0.46	0.40	0.40-0.98
5-axle**	1.09	1.25	1.05	1.67	1.11	1.05-1.67	1.07	1.17	0.97	0.77	0.63	0.63-1.17
6-axle or more**	1.23	1.54	1.04	2.21	1.35	1.04-2.21	1.05	1.19	0.90	0.64	...	0.64-1.19
All multiple units	1.04	1.21	0.97	1.52	1.08	0.97-1.52	1.05	0.96	0.91	0.67	0.53	0.53-1.05
All trucks	0.52	0.38	0.21	0.30	0.12	0.12-0.52	0.39	0.23	0.21	0.07	0.24	0.07-0.39

**Compiled from data supplied by the Highway Statistics Division, U.S. Federal Highway Administration.*
***Including full-trailer combinations in some states.*
****See Article 4.05 for values to be used when the number of heavy trucks is low.*

$$ESAL = AADT \times HVP \times DF \times TF \times TDY$$

$$Cumulative\ ESALs = Initial\ year\ ESAL_{(Design\ Lane)} \times \frac{[(1+g)^t - 1]}{g}$$

$$\Delta PSI = p_o - p_t \qquad u_f = 1.18 \times 10^8 M_R^{-2.32}$$

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + \cdots + a_i D_i m_i$$

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

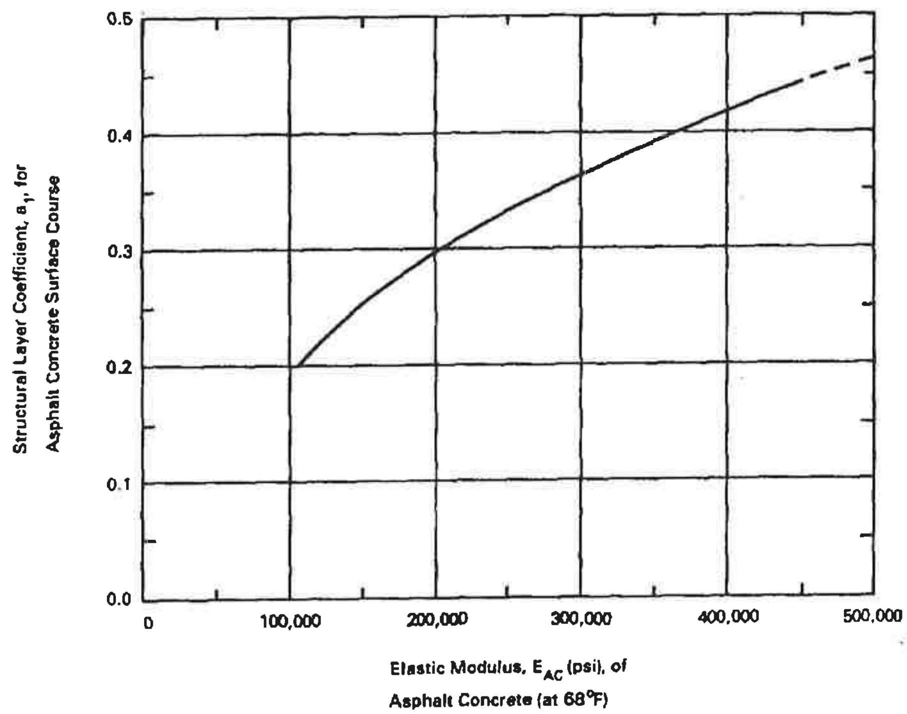
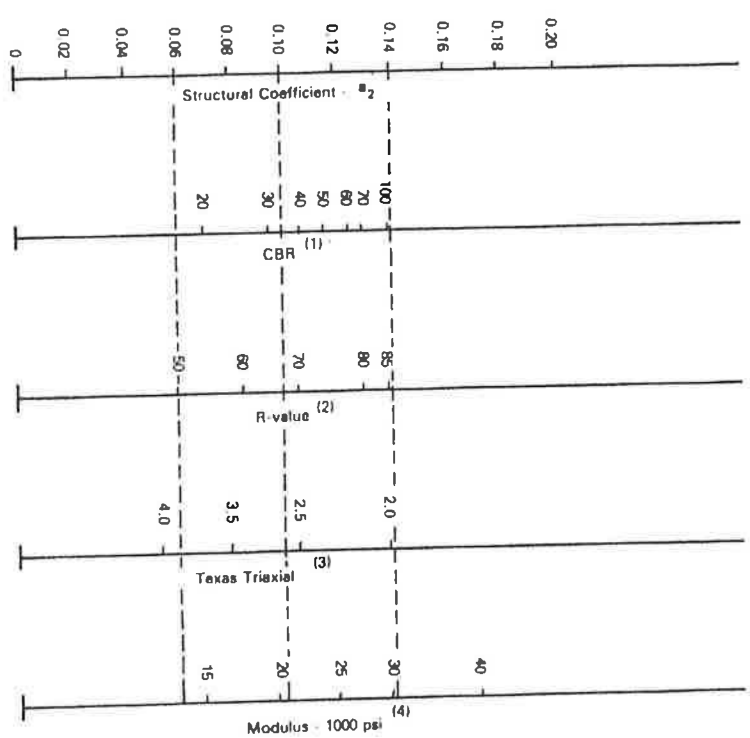
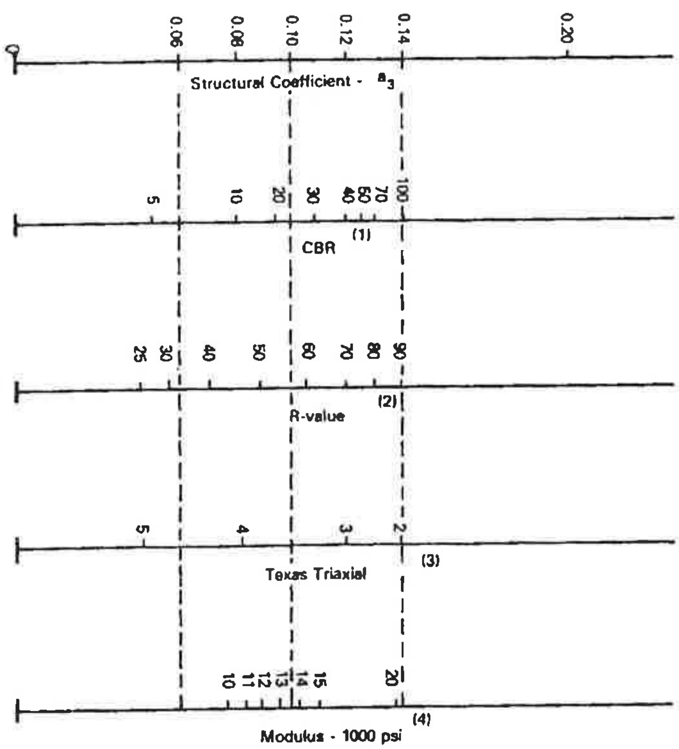


Figure 2.5. Chart for Estimating Structural Layer Coefficient of Dense-Graded Asphalt Concrete Based on the Elastic (Resilient) Modulus (*3*)



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project (*3*).

Figure 2.6. Variation in Granular Base Layer Coefficient (a_2) with Various Base Strength Parameters (*3*)



(1) Scale derived from correlations from Illinois.
(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.
(3) Scale derived from correlations obtained from Texas.
(4) Scale derived on NCHRP project (3).

Figure 2.7. Variation in Granular Subbase Layer Coefficient (a_3) with Various Subbase Strength Parameters (3)

Minimum Thickness (inches)

Traffic, ESAL's	Asphalt Concrete	Aggregate Base
Less than 50,000	1.0 (or surface treatment)	4
50,001–150,000	2.0	4
150,001–500,000	2.5	4
500,001–2,000,000	3.0	6
2,000,001–7,000,000	3.5	6
Greater than 7,000,000	4.0	6

Table 20.16 Suggested Levels of Reliability for Various Functional Classifications

	Recommended Level of Reliability	
Functional Classification	*Urban*	*Rural*
Interstate and other freeways	85–99.9	80–99.9
Other principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Table 2.4. Recommended m_i Values for Modifying Structural Layer Coefficients of Untreated Base and Subbase Materials in Flexible Pavements

	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	**Less Than 1%**	**1–5%**	**5–25%**	**Greater Than 25%**
Excellent	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	1.05–0.95	0.95–0.75	0.75–0.40	0.40

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R * S_o + 9.36*\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32*\log_{10} M_R - 8.07$$

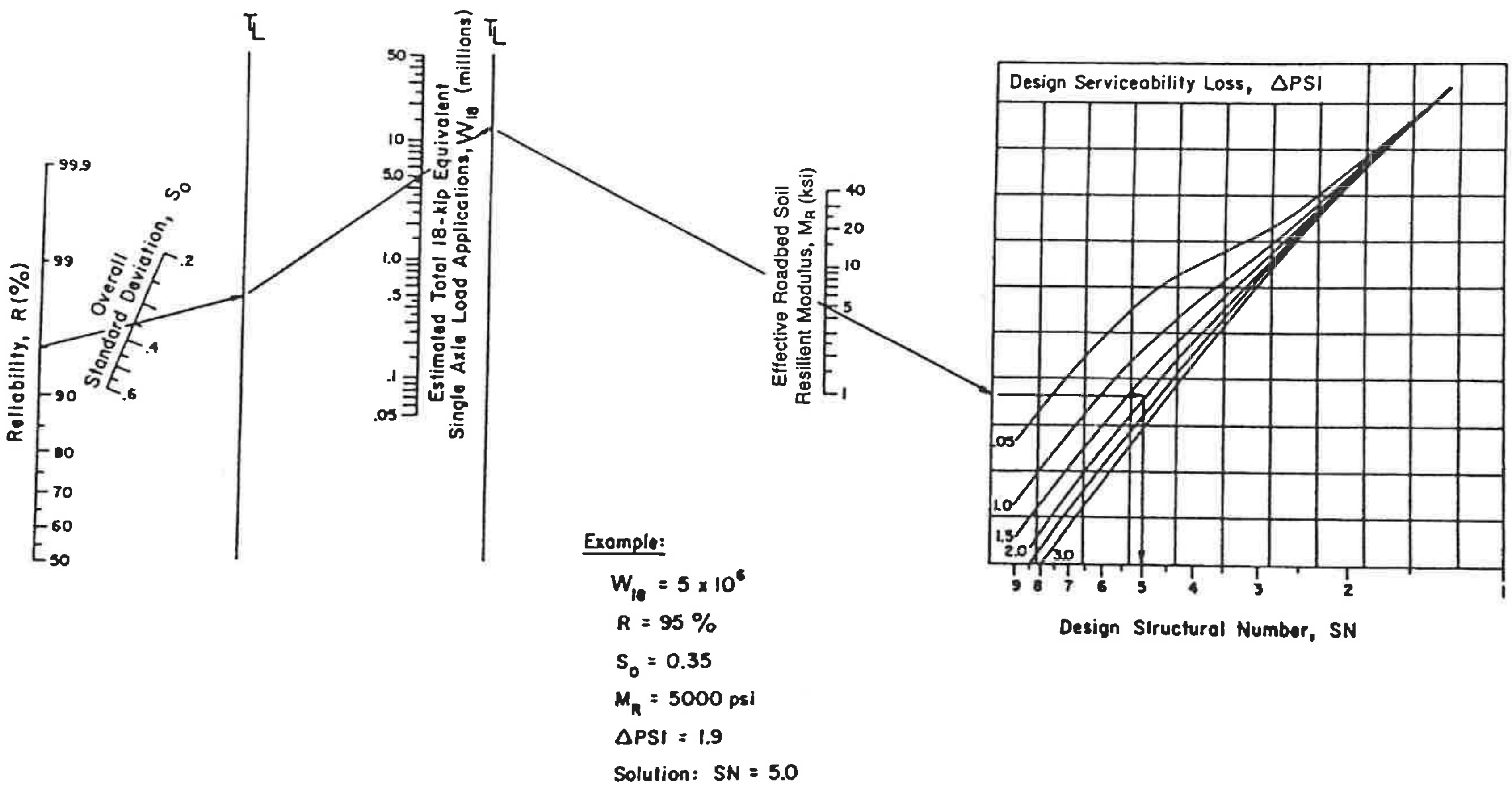


Figure 3.1. Design Chart for Flexible Pavements Based on Using Mean Values for Each Input

AASTO Rigid Pavement Design

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R * S_o + 7.35*\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5 - 1.5}\right]}{1 + \frac{1.624*10^7}{(D+1)^{8.46}}} + (4.22-0.32p_t)*\log_{10}\left[\frac{S_c' * C_d\left[D^{0.75} - 1.132\right]}{215.63*J\left[D^{0.75} - \frac{18.42}{(E_c/k)^{0.25}}\right]}\right]$$

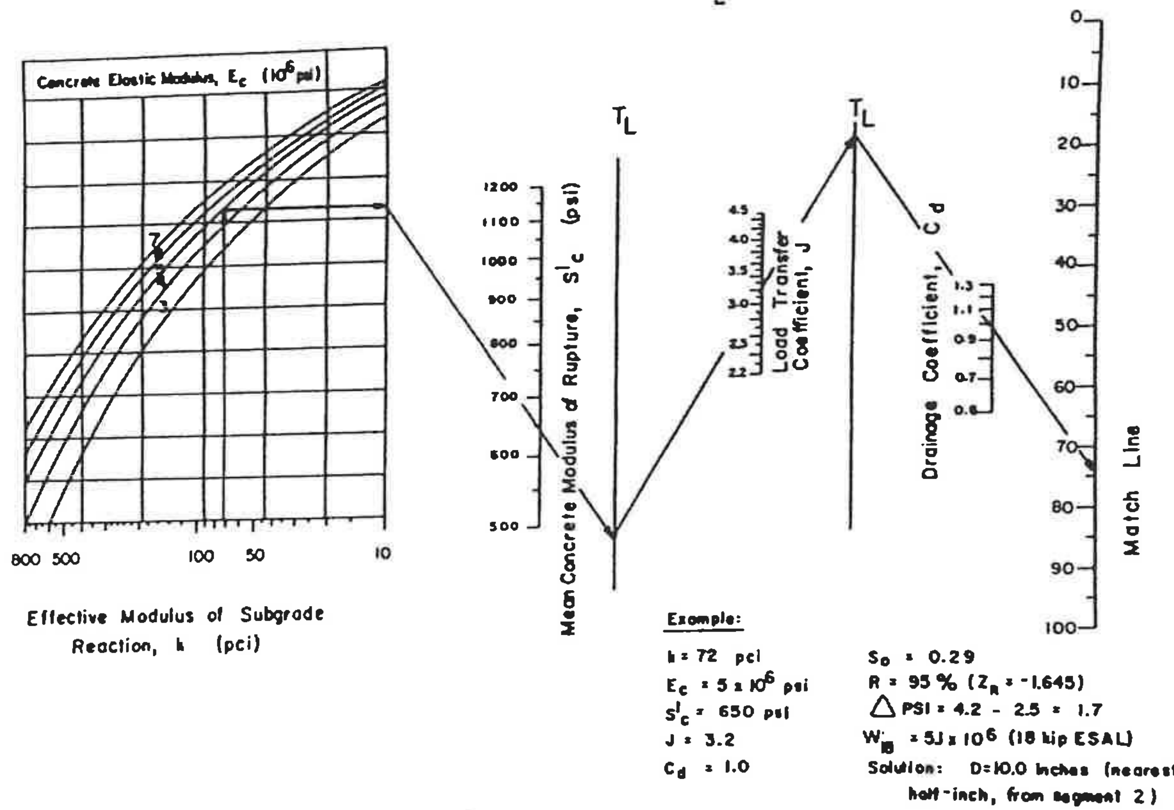


Figure 3.7. Design Chart for Rigid Pavement Based on Using Mean Values for Each Input Variable (Segment 1)

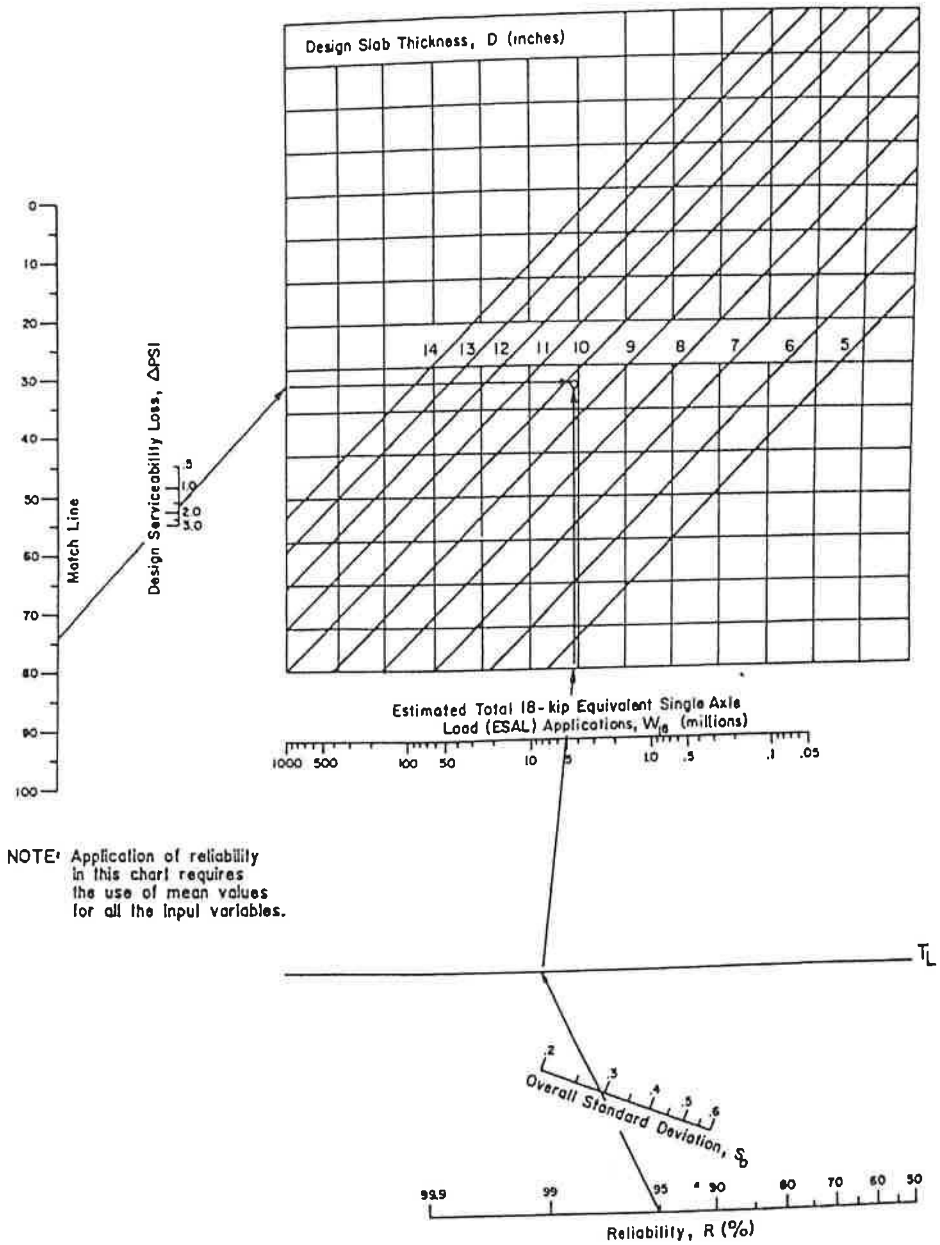


Figure 3.7. Continued—Design Chart for Rigid Pavements Based on Using Mean Values for Each Input Variable (Segment 2)

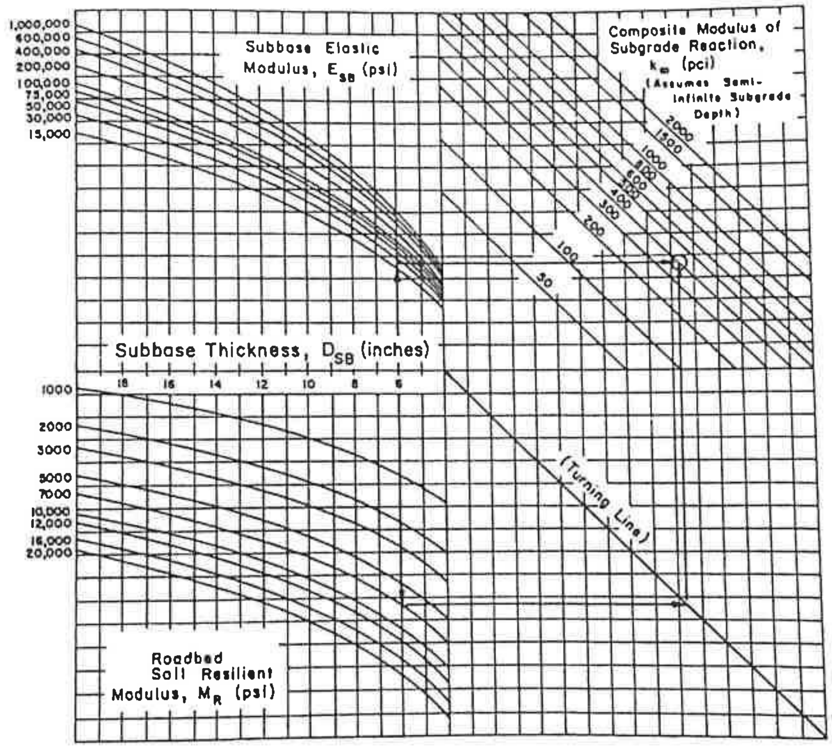


Figure 3.3. **Chart for Estimating Composite Modulus of Subgrade Reaction, k_∞, Assuming a Semi-Infinite Subgrade Depth.** (For practical purposes, a semi-infinite depth is considered to be greater than 10 feet below the surface of the subgrade.)

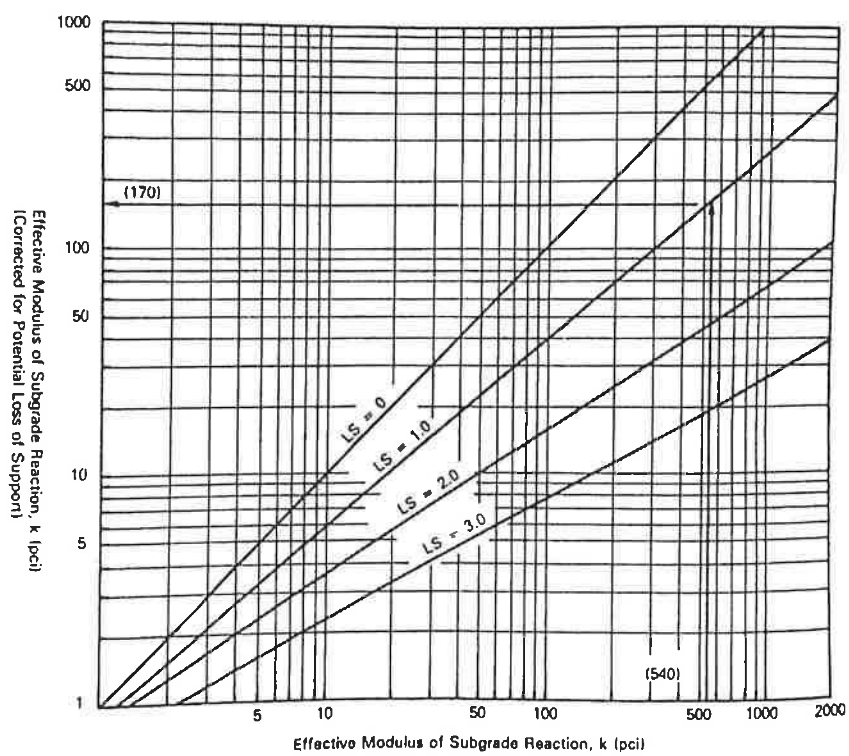


Figure 3.6. **Correction of Effective Modulus of Subgrade Reaction for Potential Loss of Subbase Support (6**

$Ec = 57{,}000\ (f'_c)^{0.5}$	$\Delta PSI = p_o - p_t$
$k = M_R / 19.4$ *When no subbase is used*	$u_f = (D^{0.75} - 0.93\ k^{-0.25})^{3.42}$

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R * S_o + 7.35 * \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5 - 1.5}\right]}{1 + \frac{1.624*10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) * \log_{10}\left[\frac{S'_c * C_d \left[D^{0.75} - 1.132\right]}{215.63 * J \left[D^{0.75} - \frac{18.42}{(E_c/k)^{0.25}}\right]}\right]$$

Table 2.5. Recommended Values of Drainage Coefficient, C_d, for Rigid Pavement Design

Quality of Drainage	Percent of Time Pavement Structure Is Exposed to Moisture Levels Approaching Saturation: Less Than 1%	1–5%	5–25%	Greater Than 25%
Excellent	1.25–1.20	1.20–1.15	1.15–1.10	1.10
Good	1.20–1.15	1.15–1.10	1.10–1.00	1.00
Fair	1.15–1.10	1.10–1.00	1.00–0.90	0.90
Poor	1.10–1.00	1.00–0.90	0.90–0.80	0.80
Very poor	1.00–0.90	0.90–0.80	0.80–0.70	0.70

Table 20.16 Suggested Levels of Reliability for Various Functional Classifications

Functional Classification	*Recommended Level of Reliability*: *Urban*	*Rural*
Interstate and other freeways	85–99.9	80–99.9
Other principal arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

Table 2.6. Recommended Load Transfer Coefficient for Various Pavement Types and Design Conditions

Shoulder	Asphalt		Tied P.C.C.	
Load Transfer Devices	**Yes**	**No**	**Yes**	**No**
Pavement Type				
1. Plain jointed and jointed reinforced	3.2	3.8–4.4	2.5–3.1	3.6–4.2
2. CRCP	2.9–3.2	N/A	2.3–2.9	N/A

Type of Material	Loss of Support (LS)
Cement Treated Granular Base (E = 1,000,000 to 2,000,000 psi)	0.0 to 1.0
Cement Aggregate Mixtures (E = 500,000 to 1,000,000 psi)	0.0 to 1.0
Asphalt Treated Base (E = 350,000 to 1,000,000 psi)	0.0 to 1.0
Bituminous Stabilized Mixtures (E = 40,000 to 300,000 psi)	0.0 to 1.0
Lime Stabilized (E = 20,000 to 70,000 psi)	1.0 to 3.0
Unbound Granular Materials (E = 15,000 to 45,000 psi)	1.0 to 3.0
Fine Grained or Natural Subgrade Materials (E = 3,000 to 40,000 psi)	2.0 to 3.0

Note: E in this table refers to the general symbol for elastic or resilient modulus of the material.

	Standard Deviation, S_o
Flexible pavements	0.40–0.50
Rigid pavements	0.30–0.40

Highway Geometric Design

$d_b = \dfrac{v^2}{2g(f+G)}$		$K = \dfrac{L}{\Delta G}$
$L_{crest} = \dfrac{SSSD^2 \times A}{200(H + h_1 + 2\sqrt{H \times h_1})}$		$K = \dfrac{SSSD^2}{200(\sqrt{H} + \sqrt{h_1})^2}$
$L_{sag} = \dfrac{SSSD^2 \times A}{200(H + SSSD\ Tan\beta)}$		$\dfrac{Gv^2}{gR} cos\gamma = Gsin\gamma + G(cos\gamma)\mu$
$\dfrac{v^2}{gR} = e + \mu$		$R = \dfrac{V^2}{127(e+\mu)}$
$A^2 = L_s R = \dfrac{2RV \times 1000}{3600}$		$A = \sqrt{0.03577V^3}$
$L_s = \dfrac{we}{2s}$	$A^2 = R \times L$	$A = \sqrt{\dfrac{RV}{1.8}}$
$S = 2R\theta° \left(\dfrac{\pi}{180}\right)$		$\theta = \dfrac{28.65}{R} S$
$m = R(1 - \cos \dfrac{28.65}{R} S)$		

Relative Slope Values

Design speed (km/h)	60	80	90	≥ 100
Relative slope (m/m)	0.006	0.0051	0.0047	0.0044

Clear zone distances for straight sections (m)

Design Speed (km/h)	Design ADT	6:1 or flatter	Fill Slopes 5:1 to 4:1	3:1	3:1	Cut Slopes 5:1 to 4:1	6:1 or flatter
≤ 60	< 750	2.0 - 3.0	2.0 - 3.0	see note	2.0 - 3.0	2.0 - 3.0	2.0 - 3.0
	750 - 1500	3.0 - 3.5	3.5 - 4.5	see note	3.0 - 3.5	3.0 - 3.5	3.0 - 3.5
	1500 - 6000	3.5 -4.5	4.5 - 5.0	see note	3.5 -4.5	3.5 -4.5	3.5 -4.5
	> 6000	4.5 -5.0	5.0 - 5.5	see note	4.5 -5.0	4.5 -5.0	4.5 -5.0
70 - 80	< 750	3.0 - 3.5	3.5 - 4.5	see note	2.5 - 3.0	2.5 - 3.0	3.0 - 3.5
	750 - 1500	4.5 - 5.0	5.0 - 6.0	see note	3.0 - 3.5	3.5 - 4.5	4.5 - 5.0
	1500 - 6000	5.0 - 5.5	6.0 - 8.0	see note	3.5 - 4.5	4.5 - 5.0	5.0 - 5.5
	> 6000	6.0 - 6.5	7.5 - 8.5	see note	4.5 - 5.0	5.5 - 6.0	6.0 - 6.5
90	< 750	3.5 - 4.5	4.5 - 5.5	see note	2.5 - 3.0	3.0 - 3.5	3.0 - 3.5
	750 - 1500	5.0 - 5.5	6.0 - 7.5	see note	3.0 - 3.5	4.5 - 5.0	5.0 - 5.5
	1500 - 6000	6.0 - 6.5	7.5 - 9.0	see note	4.5 - 5.0	5.0 - 5.5	6.0 - 6.5
	> 6000	6.5 - 7.5	8.0 - 10.0	see note	5.0 - 5.5	6.0 - 6.5	6.5 - 7.5
100	< 750	5.0 - 5.5	6.0 - 7.5	see note	3.0 - 3.5	3.5 - 4.5	4.5 - 5.0
	750 - 1500	6.0 - 7.5	8.0 - 10.0	see note	3.5 - 4.5	5.0 - 5.5	6.0 - 6.5
	1500 - 6000	8.0 - 9.0	10.0 - 12.0	see note	4.5 - 5.5	5.5 - 6.5	7.5 - 8.0
	> 6000	9.0 - 10.0	11.0 - 13.5	see note	6.0 - 6.5	7.5 - 8.0	8.0 - 8.5
≥ 110	< 750	5.5 - 6.0	6.0 - 8.0	see note	3.0 - 3.5	4.5 - 5.0	4.5 - 4.9
	750 - 1500	7.5 - 8.0	8.5 - 11.0	see note	3.5 - 5.0	5.5 - 6.0	6.0 - 6.5
	1500 - 6000	8.5 - 10.0	10.5 - 13.0	see note	5.0 - 6.0	6.5 - 7.5	8.0 - 8.5
	> 6000	9.0 - 10.5	11.5 - 14.0	see note	6.5 - 7.5	8.0 - 9.0	8.5 - 9.0

Clear zone correction factors in curves

Radius (m)	Design Speed 60	70	80	90	100	110+
900	1.1	1.1	1.1	1.2	1.2	1.2
700	1.1	1.1	1.2	1.2	1.2	1.3
600	1.1	1.2	1.2	1.2	1.3	1.4
500	1.1	1.2	1.2	1.3	1.3	1.4
450	1.2	1.2	1.3	1.3	1.4	1.5
400	1.2	1.2	1.3	1.3	1.4	
350	1.2	1.2	1.3	1.4	1.5	
300	1.2	1.3	1.4	1.5	1.5	
250	1.3	1.3	1.4	1.5		
200	1.3	1.4	1.5			
150	1.4	1.5				
100	1.5					

Note: The clear zone horizontal curve adjustment factor is applied to the outside of curves only. Curve flattor than 900 m do not require an adjusted clear zone.

Friction Coefficients to be used when needed

Vehicle Speed (km/h)	≤ 60	70	80	90	100	110	120
Stopping Coefficient of Friction	0.38	0.37	0.35	0.31	0.30	0.28	0.27
Coefficient of Side Friction	0.17	0.16	0.15	0.12	0.11	0.09	0.07