UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 5 Examination in Engineering: August 2018

Module Number: CE5302 **Module Name: Highway Engineering Design**

[Three Hours]

[Answer all questions. Each question carries TWELVE marks]

Main equations which may be needed are attached to this paper

All Standard Notations denote their regular meanings

Q1. Existing two-lane Mattakkuliya-Negombo highway is proposed to be upgraded as a four-lane highway in order to meet the traffic flow demand in the northern corridor of Colombo by increasing the capacity of the highway.

a) Define what is meant by "Highway Capacity"

[1.0 Mark]

b) Identify four road related factors that influence the free flow speed achievable by a given vehicle driver combination.

[2.0 Marks]

c) A specific upgrade section of Mattakkuliya-Negombo highway, stated above, with a grade of 2.5% and length of 0.75 miles is widely criticized in the mass media for traffic congestion. In the capacity of a Highway Engineer, you have been requested to assess the capacity and level of service under existing conditions.

According to traffic data of Road Development Authority(RDA), the highway section has a total traffic of 5240 pc/hr. This section consists of four lanes with a lane width of 10.5 ft. Moreover, no centre median is present and the boundary of the built area is just on the outer edges of carriageway.

The posted speed in this section of the road is 55 miles/hr and no signal-controlled junctions present in the vicinity. Access density is 10 points per mile. Traffic is composed of 10% trucks, 5% recreational vehicles and rest being motor cars.

Most drivers are daily commuters to the downtown of Colombo. Traffic flow has a PHF of 0.8 and directional split of 50/50. You may use the data provided in the Table Q1-1 to Table Q1-10 to answer these questions.

i. Determine the capacity and level of service (LOS) of the highway section.

ii. In the proposed rehabilitation project, it is proposed to increase a width of the lane from 10.5 ft to 12.2 ft as the only change in the geometric design. Check whether the proposed change has any impact on the capacity and level of service. The demand volume and the composition of vehicles and drivers will not be changed.

[9.0 Marks]

Q2. Wearing course of the in the proposed four-lane Mattakkuliya-Negombo highway, stated in above question, is to be made of hot mix asphalt (HMA) concrete which is to be designed using the Marshall mix procedure.

a) Use the information in Table Q2-1 to determine the:

 i. bulk specific gravity of the combined aggregates;
 ii. effective specific gravity of the combined aggregates;
 iii. percentage of absorbed asphalt binder;
 iv. effective asphalt binder content;
 v. voids in the mineral aggregate;
 vi. percentage of air voids in the mixture; and
 vii. voids filled with asphalt binder.

[7.0 Marks]

b)
 i. Identify the two methods of classifying asphalt cement.
 ii. Briefly describe what is meant by "60/70" bitumen.
 iii. What is meant by "Asphalt Cutback "?
 iv. List the three types of cutbacks.
 v. Identify most suitable types for prime coat and tack coat.

[5.0 Marks]

Q3. A left-hand horizontal curve having a total deviation of 36° in the proposed four-lane Mattakkuliya-Negombo highway, stated in above questions, is required to be designed as a spiral-circle-spiral composite curve with a design speed of 100 km/h. The two spiral curves are designed to be 100 m in length. Spiral curves are designed to meet a maximum rate of increase in lateral acceleration of 0.3 m/s^3, maximum 1 m shift in the circular curve and to have a maximum rate of pavement rotation of 2.5 %/s. The circular part of the curve is designed to be a 6° (based on 100m arc definition) curve. Normal cross fall of 1% is employed while the maximum super elevation is set at 4% for this highway.

a) Briefly explain three advantages of having a spiral-circle-spiral composite curve over a simple circular curve between two given tangents.

[3.0 Marks]

b) Check whether the design lengths of the spirals are enough to fully achieve the advantages you stated (a) above.

[3.0 Marks]

c) Assuming that the designer is sticking with 100 m spiral curves determine the length of the circular portion of the curve.

[2.5 Marks]

d) If the lateral friction coefficient is 0.15 what should be the super elevation rate applied to this curve?

[2.0 Marks]

e) If the meeting point of tangent and spiral (TS) is having a chainage of 20+222.00 determine the chainages of all important points (SC, CS and ST) along the curve.

[1.5 Marks]

Q4. A 10 km segment of the proposed four-lane Mattakkuliya-Negombo highway, stated in above questions, is required to be designed as a **rigid pavement** using 'AASHTO 1993 method'. To fulfil this design requirement, current AADT and other relevant data were gathered in the 10 km segment of the existing highway. AADT along with other relevant data are shown in Table Q4-1. You may use Table Q4-2 to Table Q4-4 and nomograms given in Figure Q4-1 and Figure Q4-2 to answer the following questions.

a) List six factors which influence the annual growth rates of vehicle types.

[1.5 Marks]

b) Derive a formula for the growth factor (G_r) interms of annual growth rate (r %) and design life time (n *years*) of the highway.

[2.0 Marks]

c) Assuming a slab thickness of 10 inches, directional split of 60/40, lane utilization factor of 0.8 and a terminal serviciblity index of 2.5 determine the total 18-kip equivalent single-axle loads (W_{18}) for a 20 year design life.

[4.0 Marks]

d) The rigid pavament, stated above in this question, is to be designed with a concrete having a elastic modulus of 5×10^6 lb/in^2 and a modulus of rupture 700 lb/in^2 layed on a subgrade having a load transfer coefficient of 3.2, drainage coefficient of 1.0 and an effective modulus of subgrade reaction 100 lb/in^3. If a W_{18} value of 6×10^6 is chosen for the design, a reliability of 95% and overall standard deviation of 0.3 is assumed determine the slab thickness.

[4.5 Marks]

Q5. Major portion of the Mattakkuliya-Negombo highway, stated in above questions, is required to designed as a **flexible pavement** having three layers. In such one location the pavement layer 1 is a hot-mix asphalt (HMA) wearing course, layer 2 is an emulsion/aggregate-bituminous base, and layer 3 is a crushed stone subbase. Reliability of the flexible pavement needs to be 95% for a 20-year design life with an overall standard deviation of 0.4. Initial present serviceability index is 4.7 and the terminal serviceability index is 1.7. It is estimated that this highway will have 6×10^6 ESALs after correcting for the directional split and lane utilization.

a) When checking the reliability of a flexble pavement under AASHTO 1993 method briefly explain why one tail test is used.

[2.0 Marks]

b) Table Q5-1 shows the monthly variation of roadbed (sugrade) soil modulus at the location of design. Determine the effective roadbed soil modulus when considering an entire year.

[3.0 Marks]

c) The effective modulus of layer 1, layer 2 and layer 3 are determined to be 400×10^3 lb/in^2 , 30×10^3 lb/in^2 and 11×10^3 lb/in^2 respectively. If the moisture coeeficient of layer 1, layer 2 and layer 3 are 1.0, 0.9 and 0.8 determine the layer thicknesses of all three layers at the location stated above b) using the nomogram in shown in Figure Q5-1 or the corresponding equation.

[7.0 Marks]

Equations that may be useful in the calculations

$$G_{se} = \frac{P_{mm} - P_b}{P_{mm}/G_{mm} - P_b/G_b}$$

$$L = 2d_s - \frac{200 \times (\sqrt{h_1} + \sqrt{h_2})^2}{|G_2 - G_1|}$$

$$K = \frac{|G_2 - G_1|}{L}$$

$$S_n = \frac{(1 + r)^n - 1}{r}$$

$$G_{sb} = \frac{P_1 + P_2 + P_3}{P_1/G_1 + P_2/G_2 + P_3/G_3}$$

$$P_{ba} = \frac{(G_{se} - G_{sb})}{G_{sb} \times G_{se}} \times G_b \times 100$$

$$P_{be} = P_b - \frac{P_{ba}}{100} \times P_s$$

$$P_a = \frac{(G_{mm} - G_{mb})}{G_{mm}} \times 100$$

$$U_f = 1.18 \times 10^8 \times {M_R}^{-2.32}$$

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \times P_s$$

$$VFA = \frac{VMA - P_a}{VMA} \times 100$$

$$L = |G_2 - G_1| \times k$$

$$U_f = 1.18 \times 10^8 \times {M_r}^{-2.32}$$

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A$$

$$\delta = \frac{L_s D}{200}$$

$$L_c = \frac{100\Delta}{D}$$

$$e \geq 100\left[\left(\frac{V^2}{127R}\right) - f_{lat}\right]$$

$$Q_p = q_{pk} \times h_p$$

$$Q_{tot} = Q_b + Q_p$$

$$L_s \leq \sqrt[2]{24R_c}$$

$$D_1 \geq \frac{SN_1}{a_1}$$

$$D_2 \geq \frac{(SN_2 - SN_1^*)}{a_2 m_2}$$

$$D_3 \geq \frac{(SN_3 - SN_2^* - SN_1^*)}{a_3 m_3}$$

$$L_s = \frac{e \times V}{3.6n}$$

$$L_s = \frac{e \times V}{3.6n} = \frac{V^3}{2.6 \cdot Q \cdot C \cdot R_c}$$

$$W_{18} = f_D \times f_L \times \widehat{W}_{18}$$

$$D_n \geq \frac{(SN_n - SN_{n-1}^* \cdots - SN_1^*)}{a_n m_n}$$

$$V_p = \frac{V}{PHF \times N \times f_{HV} \times f_P}$$

$$\log W_{18} = Z_R\, S_O + 9.36 \log(SN + 1) - 0.2 + \frac{\log\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.4 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \log M_R - 8.07$$

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

Table Q1-1 Limits to select FFS in Multilane Highways

Existing Free Flow Speed (mi/h)	Used Free Flow Speed (mi/h)
$42.5 \le FFS \le 47.5$	45
$47.5 \le FFS \le 52.5$	50
$52.5 \le FFS \le 57.5$	55
$57.5 \le FFS \le 62.5$	55

Table Q1-2 Equations for Speed-Flow curves in Multilane Highways

For 60 mi/h, capacity is 2,200 pc/h/ln. For 55mi/h, capacity is 2,100 pc/h/ln; for 50mi/h, 2,000 pc/h/ln; and for 45mi/h,1,900 pc/h/ln

FFS (mi/h)	For $V_p \le 1400$ pc/h/ln, S (mi/h)	For $V_p > 1400$ pc/h/ln, S (mi/h)
60	60	$60 - \left[5.00 \times \left(\frac{V_p - 1400}{800}\right)^{1.31}\right]$
55	55	$55 - \left[3.78 \times \left(\frac{V_p - 1400}{700}\right)^{1.31}\right]$
50	50	$50 - \left[3.49 \times \left(\frac{V_p - 1400}{600}\right)^{1.31}\right]$
45	45	$45 - \left[2.78 \times \left(\frac{V_p - 1400}{500}\right)^{1.31}\right]$

Table Q1-3 LOS for Multilane Highways

LOS	FFS (mi/h)	Density (pc/mi/ln)
A	All	$> 0 - 11$
B	All	$> 11 - 18$
C	All	$> 18 - 26$
D	All	$> 26 - 35$
E	60	$> 35 - 40$
	55	$> 35 - 41$
	50	$> 35 - 43$
	45	$> 35 - 45$
F	Demand Exceeds Capacity	
	60	> 40
	55	> 41
	50	> 43
	45	> 45

Table Q1-4 Adjustment to FFS for average lane width for Multilane Highways

Lane Width (ft)	Reduction in FFS, f_{LW} (mi/h)
≥12	0.0
≥11-12	1.9
≥10-11	6.6

Table Q1-5 Adjustment to FFS for Lateral Clearance for Multilane Highways

Four-Lane Highways		Six Lane-Highways	
TLC (ft)	Reduction in FFS (mi/h)	TLC (ft)	Reduction in FF(mi/h)
12	0	12	0
10	0.4	10	0.4
8	0.9	8	0.9
6	1.3	6	1.3
4	1.8	4	1.7
2	3.6	2	2.8
0	5.4	0	3.9

Note: interpolation to the nearest 0.1 is recommended.

Table Q1-6 Adjustment to FFS for Median Type for Multilane Highways

Median Type	Reduction in FFS, f_M(mi/h)
Undivided	1.6
TWLTL	0.0
Divided	0.0

Table Q1-7 Adjustment to FFS for Access Point Density for Multilane Highways

Access Point Density (access points/mi)	Reduction in FFS, f_A (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
≥40	10.0

Note: interpolation to the nearest 0.1 is recommended.

Table Q1-8 PCE for heavy vehicles in General Terrain Segments

Vehicle	PCE by Type of Terrain		
	Level	Rolling	Mountainous
Trucks and buses, E_T	1.5	2.5	4.5
RVs, E_R	1.2	2.0	4.0

Table Q1-9 PCE for RVs (E_{RV}) on Upgrades

Percentage Upgrade	Length (mi)	Proportion of RVs								
		2%	4%	5%	6%	8%	10%	15%	20%	25%
≤ 2	All	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
> 2 – 3	0.00-0.50	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.50	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
> 3 – 4	0.00-0.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.25-0.50	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
> 4 – 5	0.00-0.25	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>0.25-0.50	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	>0.50	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
> 5	0.00-0.25	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	>0.25-0.50	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	>0.50	6.0	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.0

Note: interpolation of RVs is recommended to the nearest 0.1.

Table Q1-10 PCE for Trucks and Buses (E_T) on upgrades

Upgrade (%)	*Length (mi)*	E_T — *Percentage of Trucks and Buses*								
		2	*4*	*5*	*6*	*8*	*10*	*15*	*20*	*25*
< 2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
≥ 2–3	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.50–0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.75–1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	> 1.00–1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
> 3–4	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	> 0.50–0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	> 0.75–1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 1.00–1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	> 1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
> 4–5	> 0.00–0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.50–0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	> 0.75–1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	> 1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
> 5–6	> 0.00–0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	> 0.25–0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	> 0.30–0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	> 0.50–0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	> 0.75–1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	> 1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
> 6	> 0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	> 0.25–0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	> 0.30–0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	> 0.50–0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	> 0.75–1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	> 1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

Note: interpolation of the busses and truck to the nearest 0.1 is recommended.

Q2-1

Table ~~Q3-1~~ Marshall volumetric calculation information

Material	Measured Specific gravity	Mixture composition	
		Weight of total mixture (%)	Weight of total aggregate (%)
Coarse aggregate	2.315	19.05	20
Fine aggregates	2.385	19.05	20
Stone dust	2.562	57.14	60
Bitumen binder	0.995	4.76	
Compacted sample (bulk)	2.248		
Uncompacted mixture measured maximum	2.330		

Table Q4-1 Traffic flow data along with the annual growth rates

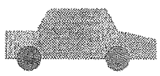
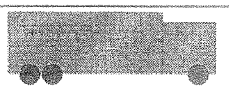
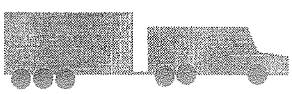
Vehicle	Axle load (lb)	Axle type	AADT	Annual growth rate (%)
	2,000	Single	20,000	3
	2,000	Single		
	10,000	Single	700	5
	22,000	Tandem		
	12,000	Single	350	1
	18,000	Tandem		
	50,000	Triple		

Table Q4-2 Axle-Load Equivalency Factors for Rigid Pavements, Single Axles, and TSI = 2.5

Axle load (kips)	Slab thickness, *D* (inches)								
	6	7	8	9	10	11	12	13	14
2	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
4	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
6	0.012	0.011	0.010	0.010	0.010	0.010	0.010	0.010	0.010
8	0.039	0.035	0.033	0.032	0.032	0.032	0.032	0.032	0.032
10	0.097	0.089	0.084	0.082	0.081	0.080	0.080	0.080	0.080
12	0.203	0.189	0.181	0.176	0.175	0.174	0.174	0.174	0.173
14	0.376	0.360	0.347	0.341	0.338	0.337	0.336	0.336	0.336
16	0.634	0.623	0.610	0.604	0.601	0.599	0.599	0.599	0.598
18	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.51	1.52	1.55	1.57	1.58	1.58	1.59	1.59	1.59
22	2.21	2.20	2.28	2.34	2.38	2.40	2.41	2.41	2.41
24	3.16	3.10	3.22	3.36	3.45	3.50	3.53	3.54	3.55
26	4.41	4.26	4.42	4.67	4.85	4.95	5.01	5.04	5.05
28	6.05	5.76	5.92	6.29	6.61	6.81	6.92	6.98	7.01
30	8.16	7.67	7.79	8.28	8.79	9.14	9.35	9.46	9.52
32	10.8	10.1	10.1	10.7	11.4	12.0	12.3	12.6	12.7
34	14.1	13.0	12.9	13.6	14.6	15.4	16.0	16.4	16.5
36	18.2	16.7	16.4	17.1	18.3	19.5	20.4	21.0	21.3
38	23.1	21.1	20.6	21.3	22.7	24.3	25.6	26.4	27.0
40	29.1	26.5	25.7	26.3	27.9	29.9	31.6	32.9	33.7
42	36.2	32.9	31.7	32.2	34.0	36.3	38.7	40.4	41.6
44	44.6	40.4	38.8	39.2	41.0	43.8	46.7	49.1	50.8
46	54.5	49.3	47.1	47.3	49.2	52.3	55.9	59.0	61.4
48	66.1	59.7	56.9	56.8	58.7	62.1	66.3	70.3	73.4
50	79.4	71.7	68.2	67.8	69.6	73.3	78.1	83.0	87.1

Source: AASHTO Guide for Design of Pavement Structures, The American Association of State Highway and Transportation Officials, Washington, DC, 1993.

Table Q4-3 Axle-Load Equivalency Factors for Rigid Pavements, Tandem Axles, and TSI =2.5

Axle load (kips)	Slab thickness, *D* (inches)								
	6	7	8	9	10	11	12	13	14
2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	0.0006	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
6	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
8	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005	0.005
10	0.015	0.014	0.013	0.013	0.012	0.012	0.012	0.012	0.012
12	0.031	0.028	0.026	0.026	0.025	0.025	0.025	0.025	0.025
14	0.057	0.052	0.049	0.048	0.047	0.047	0.047	0.047	0.047
16	0.097	0.089	0.084	0.082	0.081	0.081	0.080	0.080	0.080
18	0.155	0.143	0.136	0.133	0.132	0.131	0.131	0.131	0.131
20	0.234	0.220	0.211	0.206	0.204	0.203	0.203	0.203	0.203
22	0.340	0.325	0.313	0.308	0.305	0.304	0.303	0.303	0.303
24	0.475	0.462	0.450	0.444	0.441	0.440	0.439	0.439	0.439
26	0.644	0.637	0.627	0.622	0.620	0.619	0.618	0.618	0.618
28	0.855	0.854	0.852	0.850	0.850	0.850	0.849	0.849	0.849
30	1.11	1.12	1.13	1.14	1.14	1.14	1.14	1.14	1.14
32	1.43	1.44	1.47	1.49	1.50	1.51	1.51	1.51	1.51
34	1.82	1.82	1.87	1.92	1.95	1.96	1.97	1.97	1.97
36	2.29	2.27	2.35	2.43	2.48	2.51	2.52	2.52	2.53
38	2.85	2.80	2.91	3.03	3.12	3.16	3.18	3.20	3.20
40	3.52	3.42	3.55	3.74	3.87	3.94	3.98	4.00	4.01
42	4.32	4.16	4.30	4.55	4.74	4.86	4.91	4.95	4.96
44	5.26	5.01	5.16	5.48	5.75	5.92	6.01	6.06	6.09
46	6.36	6.01	6.14	6.53	6.90	7.14	7.28	7.36	7.40
48	7.64	7.16	7.27	7.73	8.21	8.55	8.75	8.86	8.92
50	9.11	8.50	8.55	9.07	9.68	10.14	10.42	10.58	10.66
52	10.8	10.0	10.0	10.6	11.3	11.9	12.3	12.5	12.7
54	12.8	11.8	11.7	12.3	13.2	13.9	14.5	14.8	14.9
56	15.0	13.8	13.6	14.2	15.2	16.2	16.8	17.3	17.5
58	17.5	16.0	15.7	16.3	17.5	18.6	19.5	20.1	20.4
60	20.3	18.5	18.1	18.7	20.0	21.4	22.5	23.2	23.6
63	23.5	21.4	20.8	21.4	22.8	24.4	25.7	26.7	27.3
64	27.0	24.6	23.8	24.4	25.8	27.7	29.3	30.5	31.3
66	31.0	28.1	27.1	27.6	29.2	31.3	33.2	34.7	35.7
68	35.4	32.1	30.9	31.3	32.9	35.2	37.5	39.3	40.5
70	40.3	36.5	35.0	35.3	37.0	39.5	42.1	44.3	45.9
72	45.7	41.4	39.6	39.8	41.5	44.2	47.2	49.8	51.7
74	51.7	46.7	44.6	44.7	46.4	49.3	52.7	55.7	58.0
76	58.3	52.6	50.2	50.1	51.8	54.9	58.6	62.1	64.8
78	65.5	59.1	56.3	56.1	57.7	60.9	65.0	69.0	72.3
80	73.4	66.2	62.9	62.5	64.2	67.5	71.9	76.4	80.2
82	82.0	73.9	70.2	69.6	71.2	74.7	79.4	84.4	88.8
84	91.4	82.4	78.1	77.3	78.9	82.4	87.4	93.0	98.1
86	102.0	92.0	87.0	86.0	87.0	91.0	96.0	102.0	108.0
88	113.0	102.0	96.0	95.0	96.0	100.0	105.0	112.0	119.0
90	125.0	112.0	106.0	105.0	106.0	110.0	115.0	123.0	130.0

Source: *AASHTO Guide for Design of Pavement Structures*, The American Association of State Highway and Transportation Officials, Washington, DC, 1993. Used by permission.

Table Q4-4 Axle-Load Equivalency Factors for Rigid Pavements, Triple Axles, and TSI = 2.5

Axle load (kips)	Slab thickness, *D* (inches)								
	6	7	8	9	10	11	12	13	14
2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
6	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
8	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
10	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
12	0.011	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009
14	0.020	0.018	0.017	0.017	0.016	0.01[illegible]	0.016	0.016	0.016
16	0.033	0.030	0.029	0.028	0.027	0.027	0.027	0.027	0.027
18	0.053	0.048	0.045	0.044	0.044	0.043	0.043	0.043	0.043
20	0.080	0.073	0.069	0.067	0.066	0.066	0.066	0.066	0.066
22	0.116	0.107	0.101	0.099	0.098	0.097	0.097	0.097	0.097
24	0.163	0.151	0.144	0.141	0.139	0.139	0.138	0.138	0.138
26	0.222	0.209	0.200	0.195	0.194	0.193	0.192	0.192	0.192
28	0.295	0.281	0.271	0.265	0.263	0.262	0.262	0.262	0.262
30	0.384	0.371	0.359	0.354	0.351	0.350	0.349	0.349	0.349
32	0.490	0.480	0.468	0.463	0.460	0.459	0.458	0.458	0.458
34	0.616	0.609	0.601	0.596	0.594	0.593	0.592	0.592	0.592
36	0.765	0.762	0.759	0.757	0.756	0.755	0.755	0.755	0.755
38	0.939	0.941	0.946	0.948	0.950	0.951	0.951	0.951	0.951
40	1.14	1.15	1.16	1.17	1.18	1.18	1.18	1.18	1.18
42	1.38	1.38	1.41	1.44	1.45	1.46	1.46	1.46	1.46
44	1.65	1.65	1.70	1.74	1.77	1.78	1.78	1.78	1.78
46	1.97	1.96	2.03	2.09	2.13	2.15	2.16	2.16	2.16
48	2.34	2.31	2.40	2.49	2.55	2.58	2.59	2.60	2.60
50	2.76	2.71	2.81	2.94	3.02	3.07	3.09	3.10	3.11
52	3.24	3.15	3.27	3.44	3.56	3.62	3.66	3.68	3.68
54	3.79	3.66	3.79	4.00	4.16	4.26	4.30	4.33	4.34
56	4.41	4.23	4.37	4.63	4.84	4.97	5.03	5.07	5.09
58	5.12	4.87	5.00	5.32	5.59	5.76	5.85	5.90	5.93
60	5.91	5.59	5.71	6.08	6.42	6.64	6.77	6.84	6.87
63	6.80	6.39	6.50	6.91	7.33	7.62	7.79	7.88	7.93
64	7.79	7.29	7.37	7.82	8.33	8.70	8.92	9.04	9.11
66	8.90	8.28	8.33	8.83	9.42	9.88	10.17	10.33	10.42
68	10.1	9.4	9.4	9.9	10.6	11.2	11.5	11.7	11.9
70	11.5	10.6	10.6	11.1	11.9	12.6	13.0	13.3	13.5
72	13.0	12.0	11.8	12.4	13.3	14.1	14.7	15.0	15.2
74	14.6	13.5	13.2	13.8	14.8	15.8	16.5	16.9	17.1
76	16.5	15.1	14.8	15.4	16.5	17.6	18.4	18.9	19.2
78	18.5	16.9	16.5	17.1	18.2	19.5	20.5	21.1	21.5
80	20.6	18.8	18.3	18.9	20.2	21.6	22.7	23.5	24.0
82	23.0	21.0	20.3	20.9	22.2	23.8	25.2	26.1	26.7
84	25.6	23.3	22.5	23.1	24.5	26.2	27.8	28.9	29.6
86	28.4	25.8	24.9	25.4	26.9	28.8	30.5	31.9	32.8
88	31.5	28.6	27.5	27.9	29.4	31.5	33.5	35.1	36.1
90	34.8	31.5	30.3	30.7	32.2	34.4	36.7	38.5	39.8

Source: *AASHTO Guide for Design of Pavement Structures*, The American Association of State Highway and Transportation Officials, Washington, DC, 1993. Used by permission.

Table Q5-1 Roadbed Soil Modulus

Month	Roadbed Soil Modulus MR (psi)	Month	Roadbed Soil Modulus MR (psi)
Jan	19,000	July	6,000
Feb	20,000	Aug	3,000
Mar	21,000	Sep	2,500
Apr	28,500	Oct	6,000
May	20,000	Nov	7,000
June	10,000	Dec	18,000

Table Q5-2 Structural-Layer Coefficients

Pavement component	Coefficient (1/inch)
Wearing surface	
Sand-mix asphaltic concrete	0.35
Hot-mix asphaltic (HMA) concrete	0.44
Base	
Crushed stone	0.14
Dense-graded crushed stone	0.18
Soil cement	0.2
Emulsion/aggregate-bituminous	0.3
Portland cement/aggregate	0.4
Lime-pozzolan/aggregate	0.4
Hot-mix asphaltic (HMA) concrete	0.4
Subbase	
Crushed stone	0.11

Explanation on imperial units

- mi= Miles= 1.609 km
- lb/in^2=Pounds per square inch=psi
- kip =A kip is a US customary unit of force. It equals 1000 pounds-force, used
- 1 kip = 4448.2216 N = 4.4482216 kN

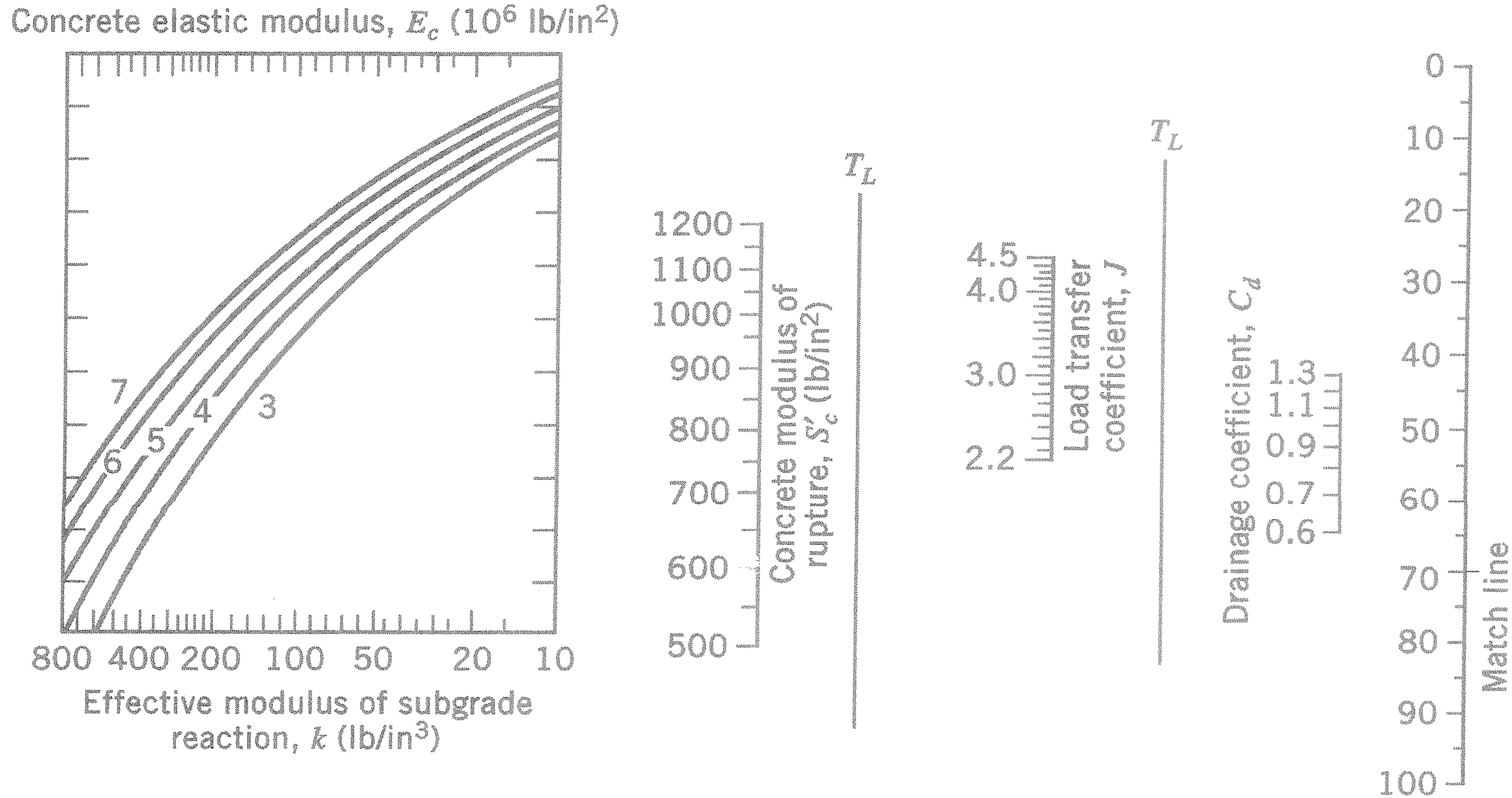


Figure Q4-1 Segment 1 of the design chart for rigid pavement based on the use of mean values for each input variable.

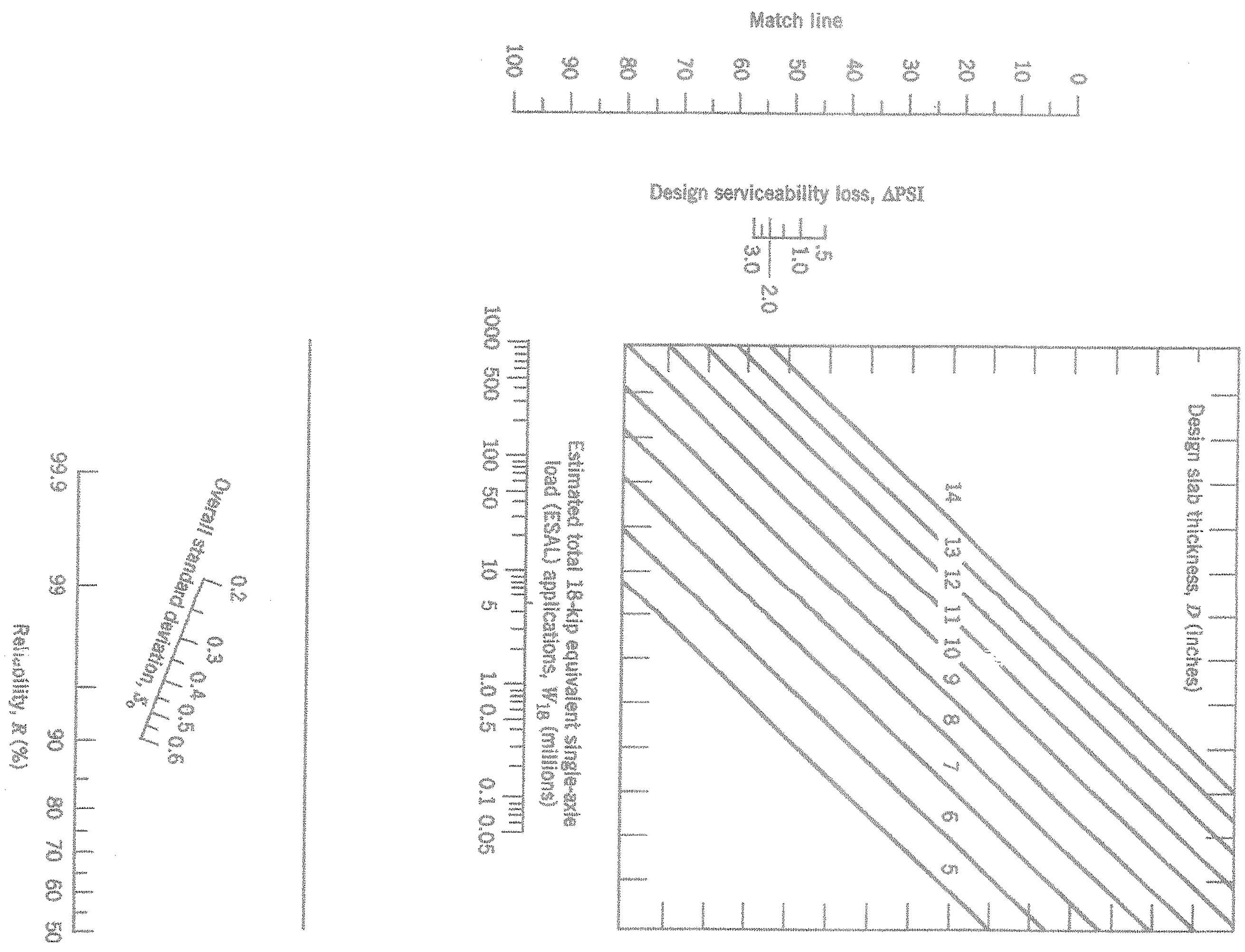


Figure Q4-2 Segment 2 of the design chart for rigid pavements based on the use of mean values for each input variable

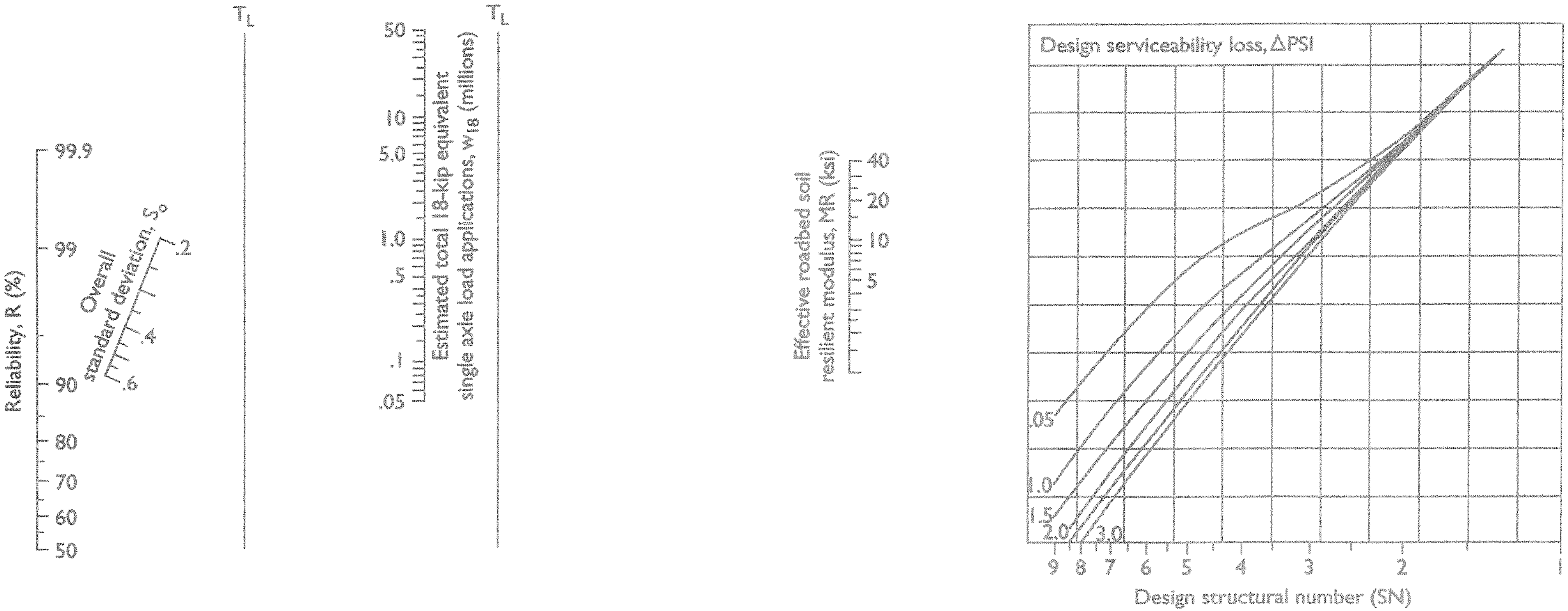


Figure Q5-1 AASHTO flexible pavement design nomograph