UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 6 Examination in Engineering: November 2022

Module Number: CE6305 **Module Name: Highway and Pavement Engineering Design (C-18)**

[Three Hours]

[Answer all questions. Each question carries **TWELVE** marks]
All Standard Notations denote their regular meanings
All equations in this paper are in imperial units unless stated otherwise

---

Q1. a) Name three topographical and three socio-economic factors each effecting the location of highway.

[3.0 Marks]

b) Draw a graph to show the variation of percent time-spent-following with two-way traffic flow in a two-lane two-way highway.

[1.0 Mark]

c) Traffic data collected for a two-lane two-way highway in rolling terrain on a peak hour are as follows. The base free-flow speed (BFFS) is the posted speed of 60 mi/h. The section length is 6 mi, lane width is 11 ft, shoulder width is 4 ft, and there are 20 access points per mi. Answer the following questions based on the data provided. In addition, you may assume reasonable values for parameters not given. You may use the Table Q1-1 to Table Q1-10 for your reference.

Volume=1600 veh/h (two-way)	Peak hour factor =0.95
Percent trucks=14	Percent directional split=50 – 50
Percent RVs=4	Percent no-passing zones=50

i. Taking the trial value for v_p as $V/_{PHF}$, compute peak 15-min hourly passenger car equivalent v_p.

ii. Compute base percent time-spent-following (BPTSF)

iii. Compute percent time-spent-following (PTSF)

iv. Compute the free-flow speed under the given conditions

v. Compute average travel speed

vi. Level of service if the segment is a Class I or Class II highway

vii. Volume-to-capacity ratio, $v/_c$

[8.0 Marks]

Q2. a) Starting from the first principles, prove that the minimum curve length for a crest curve with usual notations are given by

$$L_{min} = \frac{AS^2}{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2} for\ S < L$$

Hint: *offset to a parabola* ($y = ax^2 + bx$) *from any of its tangent is* ax^2.

[3.0 Marks]

b) A crest vertical curve is to be designed to join a 3% grade with a -2% grade at a section of a two-lane highway. Determine the minimum length of the curve if the design speed of the highway is 60 mi/h, S < L, and a perception-reaction time of 2.5 sec. The deceleration rate for braking (a) is 11.2 ft/sec^2, $h_1 = 3.5$ ft, and $h_1 = 2.0$ ft.

[3.0 Marks]

c) An existing vertical curve on a highway joins a 4.4% grade with a -4.4% grade. If the length of the curve is 275 ft. Assuming deceleration rate for braking (a) as 11.2 ft/sec^2, perception-reaction time = 2.5 sec, and that S< L determine the following.

i. the maximum safe speed on this curve
ii. speed that should be posted if 5 mph increments are used

[3.0 Marks]

d) A sag vertical curve is to be designed to join a -5% grade to a 2% grade. If the design speed is 40 mi/h, determine the minimum length of the curve that will satisfy. Assume deceleration rate for braking (a) as 11.2 ft/sec^2 and perception-reaction time of s 2.5 sec. ($H = 2ft$ and $\beta = 1°$)

[3.0 Marks]

Q3 a) Compare and contrast the bulk specific gravity and effective specific gravity of aggregates in relation to HMA.

[2.0 Marks]

b) Prove that the effective specific gravity of aggregates in a hot mix asphalt in usual notations is given by

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$

[3.0 Marks]

c) Table Q3-1 shows the data obtained in a test to determine the volumetric information of the Marshall mix, from the information, provided determine the following:

i. The bulk and effective specific gravities of the combined aggregates,
ii. The asphalt absorption,
iii. Effective asphalt binder content,
iv. Air voids,
v. VMA, and
vi. VFA of the given asphalt mixture.

[6.0 Marks]

d) Assuming that the effective specific gravity of the aggregates is constant with varying levels of asphalt content, determine the maximum specific gravity if the percent by weight of asphalt in the paving mixture is 6.2%.

[1.0 Marks]

Q4. a) Derive a formula for the growth factor (G_r) interms of annual growth rate (r %) and design lifetime (n $years$) of the highway.

[1.0 Mark]

b) A flexible pavement is designed to have SN1 to SN3 values of 2.8, 3.6 and 4.5 respectively. It consists of three layers they are hot-mix asphalt (HMA) wearing surface, dense-graded crushed stone base, and crushed stone subbase. M_2 and M_3 are equal to 0.90. Determine the layer thickness of each layer.

[3.0 Marks]

c) Traffic data collected for the highway stated in Q4.a) is shown in the Table Q4-2. If this highway is to be designed with a structural number of 4.5 for a design life of 20 years with a TSI value of 2.5. Determine the 18-kip ESAL (W_{18}) for the entire lifetime **provide your answer in Table Q4-4**found on the last page of this paper. The ELAF factors filled in the Table Q4-4 further assume f_D.and $f_L$to be equal to 1.0.

[4.0 Marks]

d) If the effective subgrade resilient modulus is 15,000 lb/in^2, the overall standard deviation is 0.5, the initial PSI is 4.7, and the TSI is 2.5, determine the reliability of the pavement design stated in Q4.a) and b)

[4.0 Marks]

Q5. A segment of a highway is to be designed as a rigid pavement using 'AASHTO 1993 method'. It is estimated that the highway will carry 5.4×10^6 ESALs in its 20-year lifetime(two-way). You may use nomograms given in Figure Q5-1 and Figure Q5-2 to answer the following questions.

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

[4.0 Marks]

b) Assuming directional split of 60/40, lane utilization factor of 0.8 determine the total 18-kip equivalent single-axle loads (W_{18}) in the design lane.

[3.0 Marks]

c) 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, design servicibility loss of 2.0, drainage coefficient of 1.0, and an effective modulus of subgrade reaction of 100 lb/in^3. If a reliability of 95% and overall standard deviation of 0.3 is assumed determine the slab thickness.

[5.0 Marks]

Equations, Figures, and Tables

Table Q1-1 Level-of-Service Criteria for Two-Lane Highways in Class I

LOS	*Percent Time-Spent-Following*	*Average Travel Speed (mi/h)*
A	≤ 35	> 55
B	> 35–50	> 50–55
C	> 50–65	> 45–50
D	> 65–80	> 40–45
E	> 80	≤ 40

Note: LOS F applies whenever the flow rate exceeds the segment capacity.

Table Q1-2 Level-of-Service Criteria for Two-Lane Highways in Class II

LOS	*Percent Time-Spent-Following*
A	≤ 40
B	40 < PTSF ≤ 55
C	55 < PTSF ≤ 70
D	70 < PTSF ≤ 85
E	> 85

Note: LOS F applies whenever the flow rate exceeds the segment capacity.

Table Q1-3 Grade Adjustment Factor (f_G) to Determine Percent Time-Spent-Following on Two-Way and Directional Segments

		Type of Terrain	
Range of Two-Way Flow Rates (pc/h)	*Range of Directional Flow Rates (pc/h)*	*Level*	*Rolling*
0–600	0–300	1.00	0.77
> 600–1200	> 300–600	1.00	0.94
> 1200	> 600	1.00	1.00

Table Q1-4 Passenger-Car Equivalents for Trucks (E_T) and RVs (E_R) to Determine Percent Time-Spent-Following on Two-Way and Directional Segments

			Type of Terrain	
Vehicle Type	*Range of Two-Way Flow Rates (pc/h)*	*Range of Directional Flow Rates (pc/h)*	*Level*	*Rolling*
Trucks, E_T	0–600	0–300	1.1	1.8
	> 600–1,200	> 300–600	1.1	1.5
	> 1,200	> 600	1.0	1.0
RVs, E_R	0–600	0–300	1.0	1.0
	> 600–1,200	> 300–600	1.0	1.0
	> 1,200	> 600	1.0	1.0

Table Q1–5 Adjustment ($f_{d/np}$) for Combined Effect of Directional Distribution of Traffic and Percentage of No-Passing Zones on Percent Time-Spent-Following on Two-Way Segments

	Increase in Percent Time-Spent-Following (%)					
	No-Passing Zones (%)					
Two-Way Flow Rate, v_p (pc/h)	*0*	*20*	*40*	*60*	*80*	*100*
Directional Split = 50/50						
≤ 200	0.0	10.1	17.2	20.2	21.0	21.8
400	0.0	12.4	19.0	22.7	23.8	24.8
600	0.0	11.2	16.0	18.7	19.7	20.5
800	0.0	9.0	12.3	14.1	14.5	15.4
1400	0.0	3.6	5.5	6.7	7.3	7.9
2000	0.0	1.8	2.9	3.7	4.1	4.4
2600	0.0	1.1	1.6	2.0	2.3	2.4
3200	0.0	0.7	0.9	1.1	1.2	1.4
Directional Split = 60/40						
≤ 200	1.6	11.8	17.2	22.5	23.1	23.7
400	0.5	11.7	16.2	20.7	21.5	22.2
600	0.0	11.5	15.2	18.9	19.8	20.7
800	0.0	7.6	10.3	13.0	13.7	14.4
1400	0.0	3.7	5.4	7.1	7.6	8.1
2000	0.0	2.3	3.4	3.6	4.0	4.3
≥ 2600	0.0	0.9	1.4	1.9	2.1	2.2
Directional Split = 70/30						
≤ 200	2.8	13.4	19.1	24.8	25.2	25.5
400	1.1	12.5	17.3	22.0	22.6	23.2
600	0.0	11.6	15.4	19.1	20.0	20.9
800	0.0	7.7	10.5	13.3	14.0	14.6
1400	0.0	3.8	5.6	7.4	7.9	8.3
≥ 2000	0.0	1.4	4.9	3.5	3.9	4.2
Directional Split = 80/20						
≤ 200	5.1	17.5	24.3	31.0	31.3	31.6
400	2.5	15.8	21.5	27.1	27.6	28.0
600	0.0	14.0	18.6	23.2	23.9	24.5
800	0.0	9.3	12.7	16.0	16.5	17.0
1400	0.0	4.6	6.7	8.7	9.1	9.5
≥ 2000	0.0	2.4	3.4	4.5	4.7	4.9
Directional Split = 90/10						
≤ 200	5.6	21.6	29.4	37.2	37.4	37.6
400	2.4	19.0	25.6	32.2	32.5	32.8
600	0.0	16.3	21.8	27.2	27.6	28.0
800	0.0	10.9	14.8	18.6	19.0	19.4
≥ 1400	0.0	5.5	7.8	10.0	10.4	10.7

Table Q1-6 Adjustment (f_{np}) for Effect of No-Passing Zones on Average Travel Speed on Two-Way Segments

	Reduction in Average Travel Speed (mi/h)					
	No-Passing Zones (%)					
Two-Way Demand Flow Rate, v_p (pc/h)	*0*	*20*	*40*	*60*	*80*	*100*
0	0.0	0.0	0.0	0.0	0.0	0.0
200	0.0	0.6	1.4	2.4	2.6	3.5
400	0.0	1.7	2.7	3.5	3.9	4.5
600	0.0	1.6	2.4	3.0	3.4	3.9
800	0.0	1.4	1.9	2.4	2.7	3.0
1000	0.0	1.1	1.6	2.0	2.2	2.6
1200	0.0	0.8	1.2	1.6	1.9	2.1
1400	0.0	0.6	0.9	1.2	1.4	1.7
1600	0.0	0.6	0.8	1.1	1.3	1.5
1800	0.0	0.5	0.7	1.0	1.1	1.3
2000	0.0	0.5	0.6	0.9	1.0	1.1
2200	0.0	0.5	0.6	0.9	0.9	1.1
2400	0.0	0.5	0.6	0.8	0.9	1.1
2600	0.0	0.5	0.6	0.8	0.9	1.0
2800	0.0	0.5	0.6	0.7	0.8	0.9
3000	0.0	0.5	0.6	0.7	0.7	0.8
3200	0.0	0.5	0.6	0.6	0.6	0.7

Table Q1-7 Grade Adjustment Factor (f_G) to Determine Average Travel Speeds on Two-Way and Directional Segments

		Type of Terrain	
Range of Two-Way Flow Rates (pc/h)	*Range of Directional Flow Rates (pc/h)*	*Level*	*Rolling*
0–600	0–300	1.00	0.71
> 600–1200	> 300–600	1.00	0.93
> 1200	> 600	1.00	0.99

Table Q1-8 Passenger-Car Equivalents for Trucks (E_T) and RVs (E_R) to Determine Speeds on Two-Way and Directional Segments

Vehicle Type	Range of Two-Way Flow Rates (pc/h)	Range of Directional Flow Rates (pc/h)	Type of Terrain: Level	Type of Terrain: Rolling
Trucks, E_T	0–600	0–300	1.7	2.5
	> 600–1,200	> 300–600	1.2	1.9
	> 1,200	> 600	1.1	1.5
RVs, E_R	0–600	0–300	1.0	1.1
	> 600–1,200	> 300–600	1.0	1.1
	> 1,200	> 600	1.0	1.1

Table Q1-9 Adjustment (f_{LS}) for Lane Width and Shoulder Width

	Reduction in FFS (mi/h)			
	Shoulder Width (ft)			
Lane Width (ft)	≥ 0 < 2	≥ 2 < 4	≥ 4 < 6	≥ 6
9 < 10	6.4	4.8	3.5	2.2
≥ 10 < 11	5.3	3.7	2.4	1.1
≥ 11 < 12	4.7	3.0	1.7	0.4
≥ 12	4.2	2.6	1.3	0.0

Table Q1-10 Adjustment (f_A) for Access-Point Density

Access Points per mi	Reduction in FFS (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
40	10.0

Table Q3-1 Volumetric Calculation Information for Marshall Mix Design

Material	Measured specific gravity	Mixture composition	
		Weight of total mixture (%)	Weight of total aggregate (%)
Coarse aggregate	2.377		60
Crushed sand	2.442		17
Natural sand	2.539		16
Mineral filler	2.727		7
Asphalt binder	0.930	2.7	
The compacted mixture, bulk	2.213		
Uncompacted mixture, measured maximum	2.355		

Table Q4-1 Structural-Layer Coefficients

Pavement component	Coefficient
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

Table Q4-2 Traffic Count Data According to FHWA Classification

FHWA Class Group	FHWA Vehicle Classification	Axle Load ($\times 10^3 lb$)		Annual Growth Rate (%)	AADT
2	Cars	Front	2.0	4.0	400
		Rear	2.0		
3	Pickup and vans	Front	8.0	6.0	500
		Rear	15.0		
4	Busses	Front	20.0	6.5	200
		Rear	30.0		
5	2 axle single unit	Front	16.0	6.5	40
		Rear	20.0		
6	3 axle single unit	Front	15.0	5.0	20
		Rear	30.0		

Table Q4-3 Cumulative Percent Probabilities of Reliability

R	0	1	2	3	4	5	6	7	8	9	9.5	9.9
90	–1.282	–1.341	–1.405	–1.476	–1.555	–1.645	–1.751	–1.881	–2.054	–2.326	–2.576	–3.080
80	–0.842	–0.878	–0.915	–0.954	–0.994	–1.036	–1.080	–1.126	–1.175	–1.227	–1.253	–1.272
70	–0.524	–0.553	–0.583	–0.613	–0.643	–0.675	–0.706	–0.739	–0.772	–0.806	–0.824	–0.838
60	–0.253	–0.279	–0.305	–0.332	–0.358	–0.385	–0.412	–0.440	–0.468	–0.496	–0.510	–0.522
50	0	–0.025	–0.050	–0.075	–0.100	–0.125	–0.151	–0.176	–0.202	–0.228	–0.241	–0.251

Useful Equations with Usual Notation

$$L_s = \frac{e_n V}{3.6n}$$

$$L_s = \frac{v^3}{3.6^3 C R_c}$$

$$L = 2S - \frac{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A} \quad for\ S > L$$

$$L_s \leq \sqrt{24R}$$

$$L = 2S - \frac{200 \times (H + S\tan(\beta))}{A} \quad for\ S > L$$

$$L = \frac{AS^2}{200 \times (H + S\tan(\beta))} \quad for\ S < L$$

$$v_p = \frac{V}{PHF \times f_{HV} \times f_G}$$

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

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

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

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

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

$$G_{mm} = \frac{100}{\frac{P_s}{G_{se}} - \frac{P_b}{G_b}}$$

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

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

$$SSD = 1.47ut + \frac{u^2}{30\left\{\left(\frac{a}{32.2}\right) - G\right\}}$$

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

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

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

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

$$L = \frac{AS^2}{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2} \quad for\ S < L$$

$$G_{sb} = \frac{P_1 + P_2 + \cdots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \cdots + \frac{P_n}{G_n}}$$

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

$$FFS = BFFS - f_{LS} - f_A$$

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

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

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

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

$$\mathrm{BPTSF} = 100[1 - e^{0.000879 \times v_p}]$$

$$\mathrm{PTSF} = \mathrm{BPTSF} + f_{d/np}$$

$$ATS = FFS - 0.0776 \times v_p - f_{np}$$

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

$$\log_{10}(W_{18}) = Z_R S_o + 9.36 \times [\log_{10}(SN + 1)] - 0.20 + \frac{\log_{10}[\Delta PSI/2.7]}{0.4 + [1094/(SN + 1)^{5.19}]} + 2.32\log_{10}(M_R) - 8.07$$

Index Number: ______________________

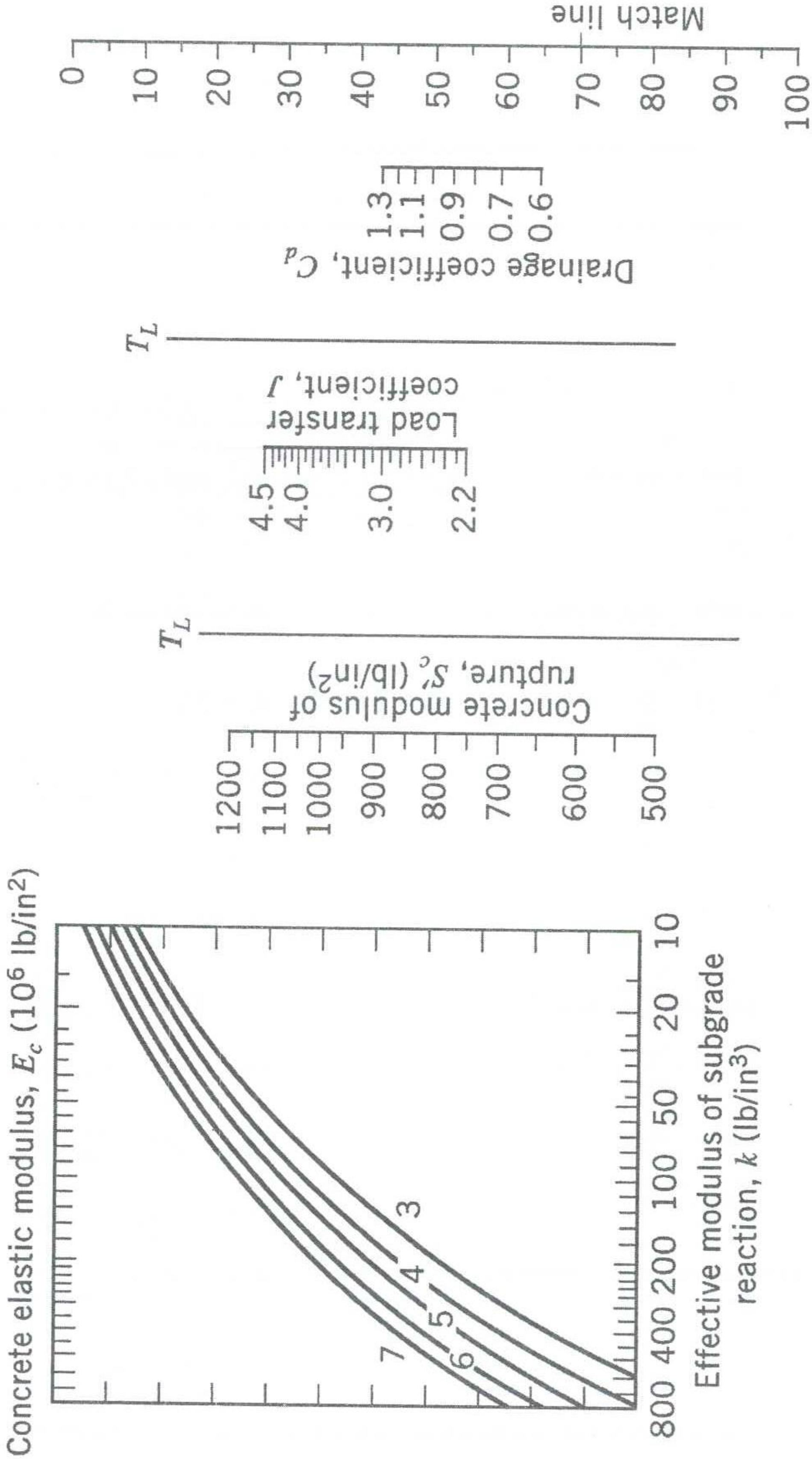

Figure Q5-1 Segment 1 of the design chart for rigid pavement based on the use of mean values for each input variable.

NOTE: Detach this and attach it to your answer script

Index Number: ______________________

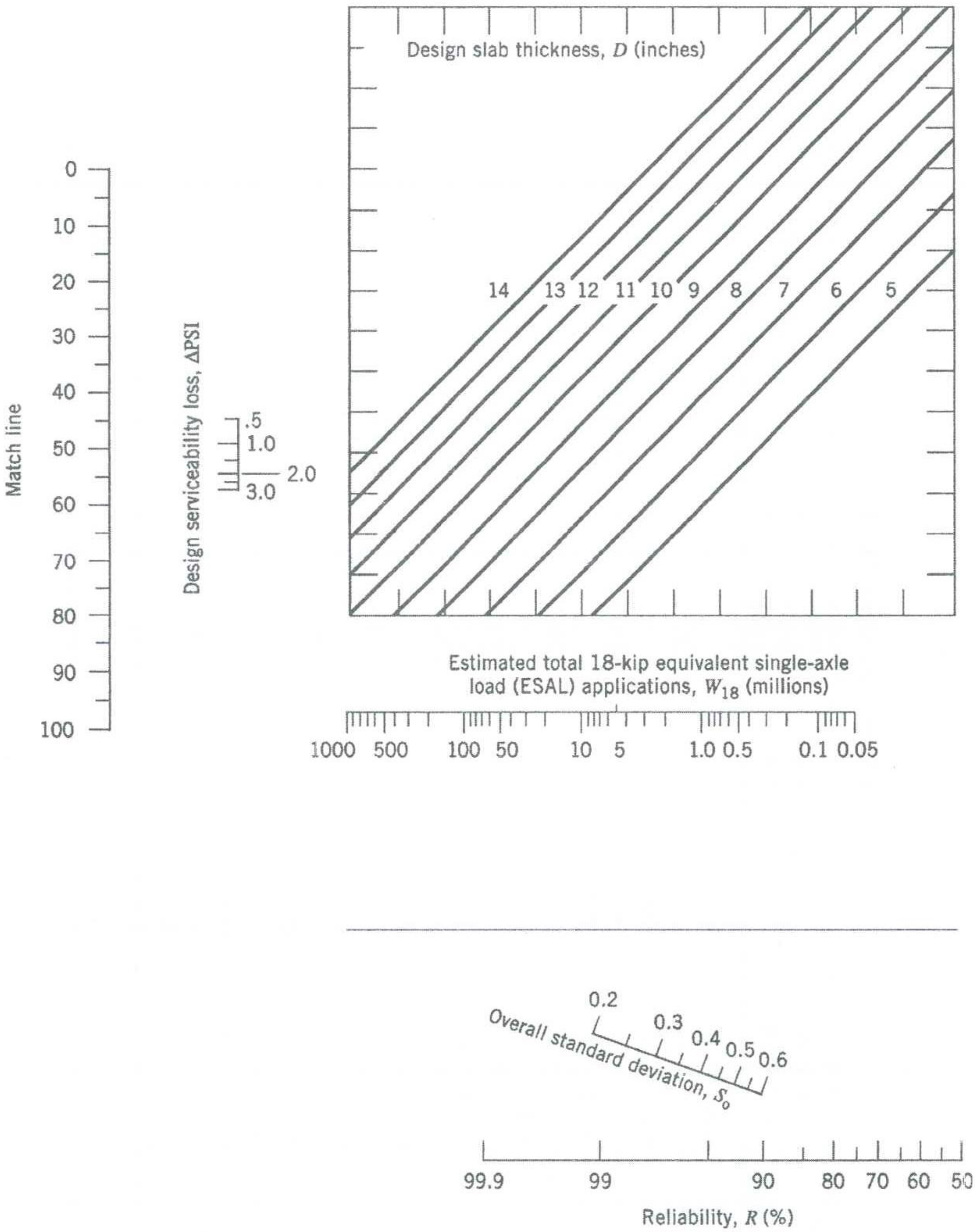

Figure Q5-2 Segment 2 of the design chart for rigid pavements based on the use of mean values for each input variable

NOTE: Detach this and attach it to your answer script

Index Number:________________

Table Q4-4 ESAL Work Sheet

FHWA Class Group	FHWA Vehicle Classification	Axle Load ($\times 10^3 lb$)		ELAF	Truck Factor	Annual Growth Rate (%)	Growth Factor	Class AADT	Class ESAL ($\widehat{W}_{18}$) $\times 10^6$
2	Cars	Front	2.0	0.0002		4.0			
		Rear	2.0	0.0002					
3	Pickup and vans	Front	8.0	0.0343		6.0			
		Rear	15.0	0.4786					
4	Busses	Front	20.0	1.5125		6.5			
		Rear	30.0	0.6583					
5	2 axle single unit	Front	16.0	0.6229		6.5			
		Rear	20.0	0.1206					
6	3 axle single unit	Front	15.0	0.4786		5.0			
		Rear	30.0	0.6583					
								Total $\widehat{W}_{18}$	

NOTE: Detach this and attach it to your answer script