National Examinations – December 2017

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. Candidates are allowed to bring ONE aid sheet 8.5" X 11" hand-written on both sides containing notes and formulae.

4. A total of **five** solutions is required. Only the first five as they appear in your answer book will be marked.

5. All questions are of equal value.

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

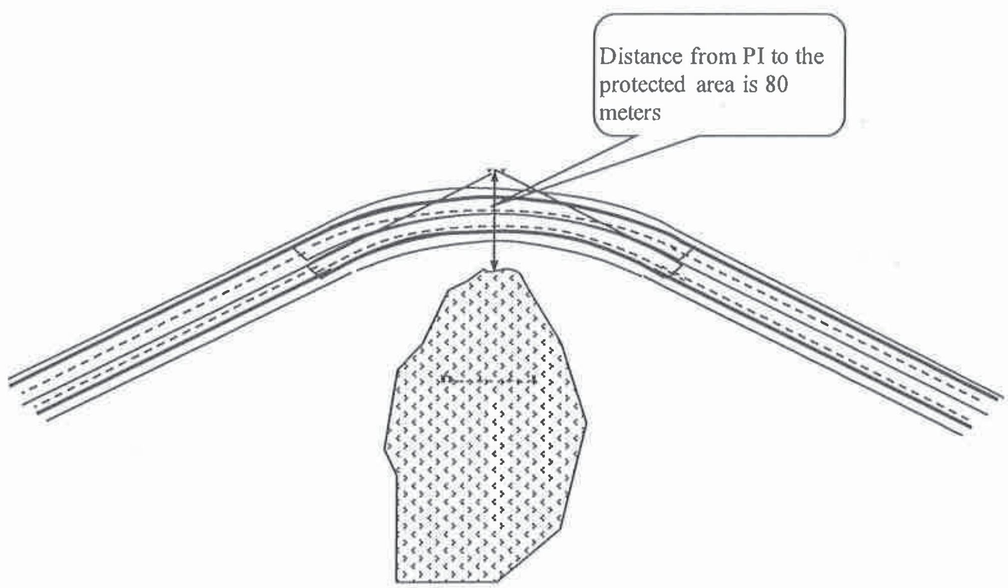
7. Tables and charts attached (5 pages)

Marking Scheme

1. (a) 8 marks; (b) 8 marks; (c) 4 marks
2. (a) 10 marks; (b) 10 marks
3. (a) 15 marks; (b) 5 marks
4. (a) 10 marks; (b) 10 marks
5. (a) 10 marks; (b) 10 marks
6. (a) 10 marks; (b) 10 marks
7. (a) 7 marks; (b) 7 marks; (c) 6 marks

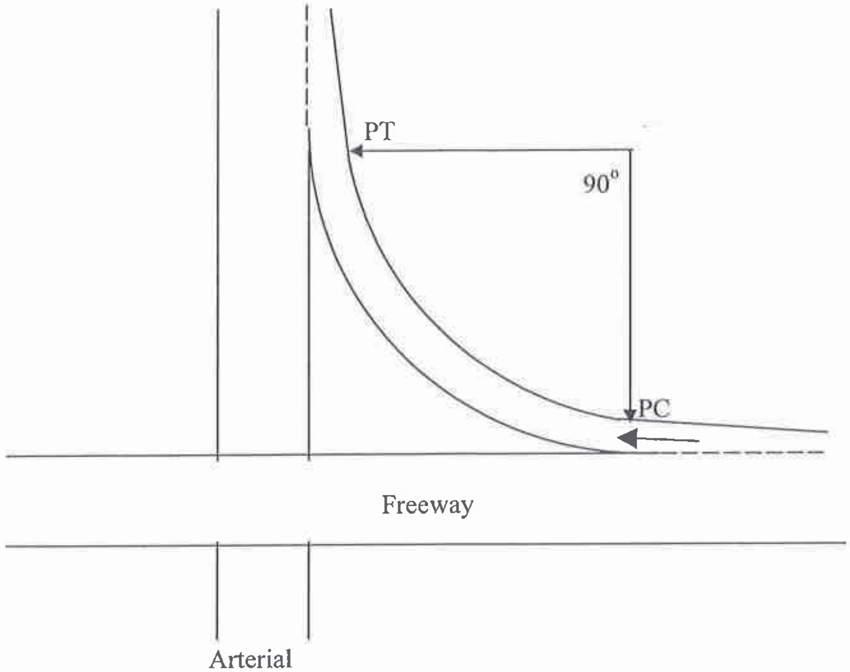
1. A new 4-lane freeway with a design speed of 120 km/h is proposed to connect two fast growing cities in Ontario. A preliminary geometric design reveals that a directional transition has to be provided at one section of the proposed highway to avoid cutting through an area protected by local environmental protection law, as shown in the following figure. The transition is designed to be located at station 2+120.000 (PI) and has an angle of intersection of 60 degrees. The distance from PI to the protected area is 80 meters. Environmental protection law regulates that the minimum distance from the edge of the highway (including the shoulder) to the protected area is 10 meters. Note that the protected area has some trees that are potential sight obstructions for the highway. The curve section has no grade and medium, and is proposed to use a superelevation rate of 0.06, and it has a lane width of 4 meters, a shoulder of 3 meters on each side.

   a) Determine the maximum radius;
   b) Verify if a reduced design speed has to be used at this section and if so what would be the recommended speed limit for this section;
   c) Determine the stationing of PT and PC.



2. An exit ramp linking a freeway to an arterial street consists a simple circular curve segment with a radius of 80 m (inner edge) and a superelevation of 0.06 (see the following figure). The ramp has a single lane with a lane width of 4.0 m. The elevations at PC and PT are 103 m and 100 m, respectively. The ramp design speed was 40 km/h. Due to the complexity of traffic conditions and environment at this intersection, the ramp was designed to provide stopping sight distance with a design perception-reaction time of 3.5 seconds.

   a) is this curve adequate for a design speed of 60 km/h if there is no sight obstruction?
   b) What distance must be cleared from the inside edge of the ramp under the design speed of 40 km/h?



3. On a vertical curve section, the following data are available:

Point	Station	Elevation
PVC	1 + 123.000	100
PVI	1 + 203.000	100
On Curve	1 + 203.000	100.60

a) What are the initial grade and final grade of the vertical curve?

b) Based on the AASHTO design standard, what is the maximum safe speed for this section (both directions)?

4. (a). A parabolic sag vertical curve is formed when a rural highway passes under a bridge joining a -6% grade to the horizontal grade. The vertical point of intersection of these two grades lies 1 meter below the curve. If the vertical clearance of the underpass is only 3.5 meters, what speed limit should be imposed at this spot?

(b). A 1200 m long sag parabolic vertical curve joins a -2.4% grade and a +3.2% grade. The point of vertical intersection is at station 10+300.000 at an elevation of 153.20 m, determine the elevations and slopes at every 100 m along the curve.

5. You are asked to design a flexible pavement structure for a new two-lane, two-way highway. The following information and design requirements are made available to you:

   - The pavement should last for 15 years with a minimum PSI of 2.5 at a probability of 70% or higher. The initial PSI is 4.5 and overall standard deviation is 0.40.
   - Several in-situ modulus tests show that the subgrade has an effective soil resilient modulus of 4000psi.
   - The traffic on this highway is composed entirely of trucks with a daily volume of 120 trucks per lane for the first year. The predicted traffic growth rate is 5.0%. Each truck has one 18-kip single axle and one 30 kip tandem axle.
   - The paving materials that are economically available for this highway includes hot-mix asphalt concrete, soil-cement and crushed stone.
   - ASSHTO pavement design method was designated as the official design method.

   a) Propose two alternative pavement structures and for each alternative determine the corresponding thickness of each layer.
   b) Following a), what would you consider in selecting the best alternative?

6. A flexible pavement has a 4 inches of hot-mix asphalt wearing surface, 6 inches of dense-graded crushed stone base, and 10 inches of crushed stone subbase. The subgrade of the pavement is clay type with an effective modulus of elasticity of 3800psi. The pavement is now 10 year old and at an PSI value of 3.0.

   a) What is the ESAL's that the pavement has carried?
   b) If the historical traffic data show that the traffic on this highway is composed entirely of trucks with average daily volume of 200 trucks. Each truck has two 20-kip single axles. What is the LEF for the 20-kip single axle?

   [You can use either Design Equation or Design Chart]

7. Briefly Answer the Following Questions:
   a) A highway engineer was hired to design a flexible pavement using AASHTO design method. Based on the available data, the expected traffic growth rate was estimated to be between 3% (lower bound) and 4% (upper bound). He decided to use growth rate of 4% to estimate cumulative ESAL's. Do you think his conservative design approach is justifiable? Why or why not?
   b) During a pavement design process using AASHTO method, an engineer noticed that the LEF value of a 40-kip tandem axle load for SN=5 is higher than for SN=4. He/she then concluded that the axle load may cause a higher damage to a pavement with a higher SN than to a pavement with a lower SN. Do you think his/her inference logic is right? Why or why not?
   c) Explain how various environmental factors are considered in AASHTO pavement design method?

Equations

Geometric Design

$SSD = V_0^2/[2g(f+G)] + V_0 t_{pr}$

$d = (V_0^2 - V_t^2)/[2g(f+G)] + V_0 t_{pr}$

Horizontal:

$R_v = V^2/[g (f_s + e)]$

$T = R \tan(\Delta/2)$; $L = \pi \Delta R / 180$; $M = R - R\cos(\Delta/2)$; $E = R / \cos(\Delta/2) - R$

$\Delta_s = 2 \cos^{-1}(1 - M_s/R_v)$

$M_s = R_v - R_v \cos[(90\, SSD)/(\pi R_v)]$

Vertical:

$y = (G_2 - G_1)/(2L)\; x^2 + G_1 x$; $Y = A x^2 / (200L)$

$S = L/2 + 100(\sqrt{H_1} + \sqrt{H_2})^2/A$ **or** $L = 2S - 200(\sqrt{H_1} + \sqrt{H_2})^2/A$ (S≥L)

$S = \sqrt{\frac{200L}{A}}(\sqrt{H_1} + \sqrt{H_2})$ **or** $L = \frac{A S^2}{200(\sqrt{H_1} + H_2)^2}$ (S<L)

$S = \frac{A L + 200H}{2A - 200\tan\beta}$ **or** $L = 2S - 200(H + S\tan\beta)/A$ (S≥L)

$S = \frac{100L\tan\beta + \sqrt{(100L\tan\beta)^2 + 200ALH}}{A}$ **or** $L = \frac{A S^2}{200(H + S\tan\beta)}$ (S<L)

$L_m = K A$ where $K = SSD^2 / 658$

$L_m = K A$ where $K = SSD^2 / (120 + 3.5\, SSD)$

Pavement Design (Flexible)

Traffic Growth Factor (TGF) = $[(1+r)^n - 1]/r$ where r = growth rate

Design ESAL's = TGF * Present Daily ESAL * 365

$SN = a_1 D_1 + a_2 D_2 M_2 + a_3 D_3 M_3$

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

Tables

1) Coefficient of friction and coefficient of side friction

Initial Vehicle Speed (km/h)	Coefficient of Friction (f)	Coefficient of Side Friction (f_s)
30	0.40	0.17
40	0.38	0.17
50	0.35	0.16
60	0.33	0.15
70	0.31	0.14
80	0.30	0.14
90	0.30	0.13
100	0.29	0.12
110	0.28	0.11
120	0.28	0.09

2) Z-statistics table

Table 4.5 Cumulative Percent Probabilities of Reliability, R, of the Standard Normal Distribution, and Corresponding Z_R

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

3) Structural layer coefficients

Pavement component	Coefficient
Wearing surface	
Sand-mix asphaltic concrete	0.35
Hot-mix asphaltic concrete	0.44
Base	
Crushed stone	0.14
Dense-graded crushed stone	0.18
Soil cement	0.20
Emulsion/aggregate-bituminous	0.30
Portland cement/aggregate	0.40
Lime-pozzolan/aggregate	0.40
Hot-mix asphaltic concrete	0.40
Subbase	
Crushed stone	0.11

4) LEF

Table 4.2 Axle-Load Equivalency Factors for Flexible Pavements, Single Axles, and TSI = 2.5

Axle load (kips)	Pavement structural number (SN)					
	1	2	3	4	5	6
2	0.0004	0.0004	0.0003	0.0002	0.0002	0.0002
4	0.003	0.004	0.004	0.003	0.002	0.002
6	0.011	0.017	0.017	0.013	0.010	0.009
8	0.032	0.047	0.051	0.041	0.034	0.031
10	0.078	0.102	0.118	0.102	0.088	0.080
12	0.168	0.198	0.229	0.213	0.189	0.176
14	0.328	0.358	0.399	0.388	0.360	0.342
16	0.591	0.613	0.646	0.645	0.623	0.606
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.3	9.5	7.9	6.8	7.0	7.8
32	13.9	12.8	10.5	8.8	8.9	10.0
34	18.4	16.9	13.7	11.3	11.2	12.5
36	24.0	22.0	17.7	14.4	13.9	15.5
38	30.9	28.3	22.6	18.1	17.2	19.0
40	39.3	35.9	28.5	22.5	21.1	23.0
42	49.3	45.0	35.6	27.8	25.6	27.7
44	61.3	55.9	44.0	34.0	31.0	33.1
46	75.5	68.8	54.0	41.4	37.2	39.3
48	92.2	83.9	65.7	50.1	44.5	46.5
50	112.0	102.0	79.0	60.0	53.0	55.0

Table 4.3 Axle-Load Equivalency Factors for Flexible Pavements, Tandem Axles, and TSI = 2.5

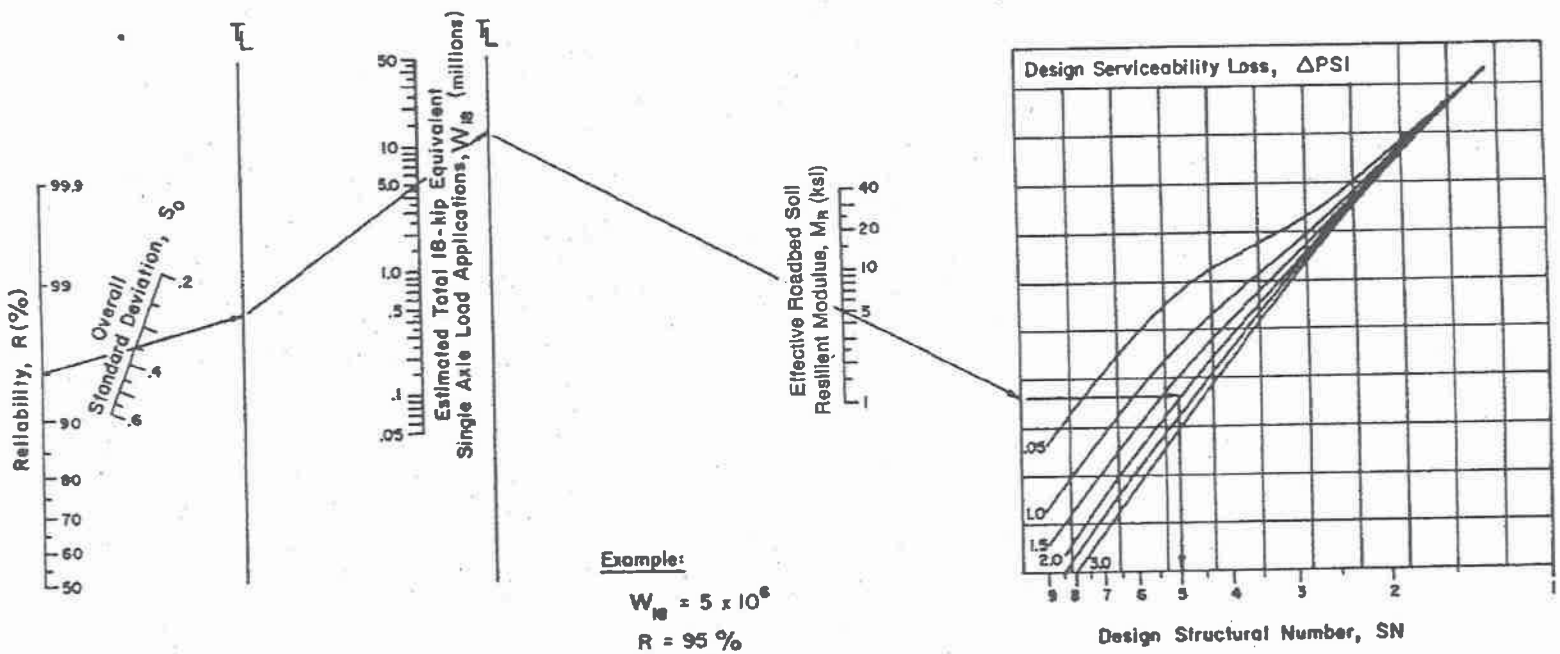
Axle load (kips)	Pavement structural number (SN)					
	1	2	3	4	5	6
2	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
4	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002
6	0.002	0.002	0.002	0.001	0.001	0.001
8	0.004	0.006	0.005	0.004	0.003	0.003
10	0.008	0.013	0.011	0.009	0.007	0.006
12	0.015	0.024	0.023	0.018	0.014	0.013
14	0.026	0.041	0.042	0.033	0.027	0.024
16	0.044	0.065	0.070	0.057	0.047	0.043
18	0.070	0.097	0.109	0.092	0.077	0.070
20	0.107	0.141	0.162	0.141	0.121	0.110
22	0.160	0.198	0.229	0.207	0.180	0.166
24	0.231	0.273	0.315	0.292	0.260	0.242
26	0.327	0.370	0.420	0.401	0.364	0.342
28	0.451	0.493	0.548	0.534	0.495	0.470
30	0.611	0.648	0.703	0.695	0.658	0.633
32	0.813	0.843	0.889	0.887	0.857	0.834
34	1.06	1.08	1.11	1.11	1.09	1.08
36	1.38	1.38	1.38	1.38	1.38	1.38
38	1.75	1.73	1.69	1.68	1.70	1.73
40	2.21	2.16	2.06	2.03	2.08	2.14
42	2.76	2.67	2.49	2.43	2.51	2.61
44	3.41	3.27	2.99	2.88	3.00	3.16
46	4.18	3.98	3.58	3.40	3.55	3.79
48	5.08	4.80	4.25	3.98	4.17	4.49
50	6.12	5.76	5.03	4.64	4.86	5.28
52	7.33	6.87	5.93	5.38	5.63	6.17
54	8.72	8.14	6.95	6.22	6.47	7.15
56	10.3	9.6	8.1	7.2	7.4	8.2
58	12.1	11.3	9.4	8.2	8.4	9.4
60	14.2	13.1	10.9	9.4	9.6	10.7
62	16.5	15.3	12.6	10.7	10.8	12.1
64	19.1	17.6	14.5	12.2	12.2	13.7
66	22.1	20.3	16.6	13.8	13.7	15.4
68	25.3	23.3	18.9	15.6	15.4	17.2
70	29.0	26.6	21.5	17.6	17.2	19.2
72	33.0	30.3	24.4	19.8	19.2	21.3
74	37.5	34.4	27.6	22.2	21.3	23.6
76	42.5	38.9	31.1	24.8	23.7	26.1
78	48.0	43.9	35.0	27.8	26.2	28.8
80	54.0	49.4	39.2	30.9	29.0	31.7
82	60.6	55.4	43.9	34.4	32.0	34.8
84	67.8	61.9	49.0	38.2	35.3	38.1
86	75.7	69.1	54.5	42.3	38.8	41.7
88	84.3	76.9	60.6	46.8	42.6	45.6
90	93.7	85.4	67.1	51.7	46.8	49.7

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

Design Equation and Chart for Flexible Pavement

NOMOGRAPH SOLVES:

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



Example:

W_{18} = 5 x 10^6

R = 95 %

S_o = 0.35

M_R = 5000 psi

ΔPSI = 1.9

Solution: SN = 5.0