**UNIVERSITY OF TORONTO**
**FACULTY OF APPLIED SCIENCE AND ENGINEERING**

FINAL EXAMINATION, DECEMBER 2001

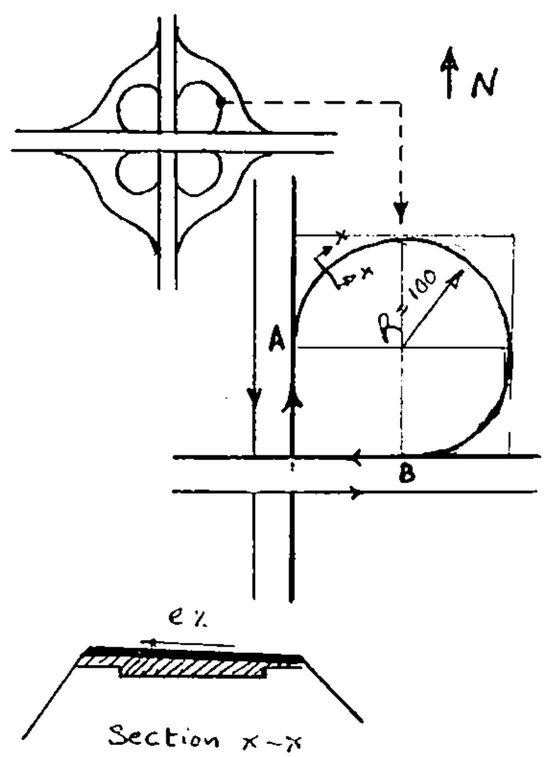
Third Year -- Program: Engineering Science
CIV354H1F – TRANSPORTARION PLANNING AND DESIGN

Exam type: D
Examiner: A. Shalaby

| Problem | Marks |
|---|---|
| 1 | 25 |
| 2 | 20 |
| 3 | 20 |
| 4 | 20 |
| 5 | 15 |
| Total | 100 |

1. The horizontal alignment of a level four-lane two-way highway segment is to be designed for a design speed of 110 km/h. The corresponding maximum allowable values for the longitudinal friction factor is 0.29 and side friction factor is 0.122. Each lane is 3.5 m wide.
   a. If the route layout suggests a curve radius of 800m, determine the design superelevation rate of the curve (the superelevation rate should not exceed 8%).
   b. For the above design, determine an appropriate length for the spiral curve and the spiral parameter, assuming a maximum rate of lateral acceleration change of 0.6 m/sec$^3$ and a maximum slope of the pavement edge relative to the center line of 0.41%. Plot a schematic showing how the superelevation is attained along the spiral curve.
   c. If the deflection angle between the two tangents of the circular curve is 80°, what change in direction will be accomplished by the two spiral curves and by the circular curve?
   d. If the highway has a 2.5m wide shoulder on each side, what should be the minimum setback of any obstacle from the shoulder edge in order to maintain the highway speed?
   e. An alternative design to that of part (a) is to maintain the tangent's crown slope of 2% along the curve (i.e. cross section of pavement along the circular curve is a crown section) while using the maximum allowable side friction to keep vehicles along the circular trajectory. Determine the sharpest curve radius that can be used for this design.

2. Two level freeways are grade separated as shown to the right. The elevation of the East-West freeway is 15 m higher than the North-South freeway. Both freeways are connected by a symmetric cloverleaf interchange as shown. Due to right-of-way constraints, each loop is a ¼ circle with a radius of 100m, as shown. Point A is the BVC of the sag curve and point B is the EVC of the crest curve.
   a. Design the lengths of the crest and sag curves required to (i) maintain the vertical grade of the loop as small as possible with a design speed of 80 km/h (f=0.312), and (ii) maximize the speed (assume f= 0.29)
   b. For each of the 2 cases i and ii, determine the sight distance to the top of pavement available to a driver 200 m before point B and determine the position of the driver when point B first becomes visible.



3. The earthwork quantities for a roadway section are given in Table 1.
   a. Using an appropriate scale, plot the mass diagram for the earthwork in the attached graph paper. Assume 10,000 cubic metres are available at station 0+00. (you can calculate the mass diagram ordinates directly on Table 1. If you do so, include it in your exam book).
   b. Determine the optimum haul strategies and calculate the total earthwork costs for this project using the following data:
      Free haul distance: 300m
      Excavation costs (including 300 m free haul): $\$5.50/m^3$
      Borrow (including cost of hauling): $\$12.00/m^3$
      Cost of overhaul: $5.00/station-m
      Cost of waste is included in cost of excavation

4. A Portland Cement Concrete (PCC) slab has a modulus of elasticity of 4.2 million psi and a poisson ratio of 0.25. The pavement's radius of relative stiffness is 39.72 and the modulus of subgrade reaction is 150 pci.
   a. Determine the slab thickness (use the revised Westergaard equations).
   b. Calculate the stress and deflection if a tire load of 10 k-lb (with an associated tire pressure of 90 psi) is placed on the corner of the slab.

   The pavement was designed for a 20-year life to carry traffic composed entirely of tractor semi-trailer trucks with one 16-kip single axle, one 20-kip single axle and one 35-kip tandem axle. The pavement has a concrete modulus of rupture of 800 psi, a load transfer coefficient of 3, an initial PSI of 4.5 and a terminal serviceability index of 2.5. A z-statistic of $-1.645$ and an overall standard deviation of 0.45 were used along with a drainage coefficient of 1. The highway has four northbound lanes and was conservatively designed.
   c. How many tractor semi-trailer trucks, per day, were assumed to be travelling in the northbound direction?

5. a. Describe briefly the process of the geometric design of a rural highway between two points.
   b. Describe briefly 2 types of distresses for each of flexible and rigid pavements, their causes and treatments.
   c. Derive the fundamental equation for the relationship between speed, radius, side friction factor and superelevation rate for horizontal curves.
   d. What is the main difference between flexible and rigid pavements with respect to vertical load transfer?
   e. What is the "Frost Action" phenomenon and how do we consider its effects in the design of flexible pavements?
   f. Describe the "Pumping Mechanism" and explain how we consider its effects in the design of rigid pavements.

Table 1

| Station | Cut volume | Fill volume* |
|---|---|---|
| 0 + 00 | | |
| | | 25.8 |
| 0 + 50 | | |
| | | 80.7 |
| 1 + 00 | | |
| | | 250.4 |
| 1 + 50 | | |
| | | 817.6 |
| 2 + 00 | | |
| | | 1,234.5 |
| 2 + 50 | | |
| | | 1,563.2 |
| 3 + 00 | | |
| | | 1,029.0 |
| 3 + 50 | | |
| | 63.4 | 724.5 |
| 4 + 00 | | |
| | 150.2 | 290.3 |
| 4 + 50 | | |
| | 422.6 | 54.2 |
| 5 + 00 | | |
| | 753.4 | |
| 5 + 50 | | |
| | 1,369.7 | |
| 6 + 00 | | |
| | 1,738.5 | |
| 6 + 50 | | |
| | 1,422.7 | |
| 7 + 00 | | |
| | 804.7 | 30.4 |
| 7 + 50 | | |
| | 320.5 | 190.9 |
| 8 + 00 | | |
| | 180.6 | 350.2 |
| 8 + 50 | | |
| | 75.2 | 642.4 |
| 9 + 00 | | |
| | | 963.7 |
| 9 + 50 | | |
| | | 1,284.5 |
| 10 + 00 | | |
| | | 1,669.2 |
| 10 + 50 | | |
| | | 1,891.8 |
| 11 + 00 | | |
| | | 1,527.3 |

*Corrected for 10% shrinkage.

**Table 4.7 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, copyright 1993. Used by permission.

**Table 4.11 Proportion of Directional $W_{18}$ Assumed to Be in the Design Lane**

| Number of Directional Lanes | Proportion of Directional $W_{18}$ in the Design Lane ($PDL$) |
|---|---|
| 1 | 1.00 |
| 2 | 0.80–1.00 |
| 3 | 0.60–0.80 |
| 4 | 0.50–0.75 |

✓

## Table 4.8 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, copyright 1993. Used by permission.