Solutions Manual

to accompany

***Principles of Highway Engineering and Traffic Analysis*, 4e**

By

Fred L. Mannering, Scott S. Washburn, and Walter P. Kilareski

Chapter 3
Geometric Design of Highways

U.S. Customary Units

Preface

The solutions to the fourth edition of *Principles of Highway Engineering and Traffic Analysis* were prepared with the Mathcad[1] software program. You will notice several notation conventions that you may not be familiar with if you are not a Mathcad user. Most of these notation conventions are self-explanatory or easily understood. The most common Mathcad specific notations in these solutions relate to the equals sign. You will notice the equals sign being used in three different contexts, and Mathcad uses three different notations to distinguish between each of these contexts. The differences between these equals sign notations are explained as follows.

- The ':=' (colon-equals) is an assignment operator, that is, the value of the variable or expression on the left side of ':='is set equal to the value of the expression on the right side. For example, in the statement, L := 1234, the variable 'L' is assigned (i.e., set equal to) the value of 1234. Another example is x := y + z. In this case, x is assigned the value of y + z.

- The '**=**' (bold equals) is used when the Mathcad function solver was used to find the value of a variable in the equation. For example, in the equation $5.2 \cdot t - 0.005 \cdot t^2 = 18.568 + 10 \cdot (t - 12.792)$, the **=** is used to tell Mathcad that the value of the expression on the left side needs to equal the value of the expression on the right side. Thus, the Mathcad solver can be employed to find a value for the variable 't' that satisfies this relationship. This particular example is from a problem where the function for arrivals at some time 't' is set equal to the function for departures at some time 't' to find the time to queue clearance.

- The '=' (standard equals) is used for a simple numeric evaluation. For example, referring to the x := y + z assignment used previously, if the value of y was 10 [either by assignment (with :=), or the result of an equation solution (through the use of **=**) and the value of z was 15, then the expression 'x =' would yield 25. Another example would be as follows: s := 1800/3600, with s = 0.5. That is, 's' was assigned the value of 1800 divided by 3600 (using :=), which equals 0.5 (as given by using =).

Another symbol you will see frequently is '→'. In these solutions, it is used to perform an evaluation of an assignment expression in a single statement. For example, in the following statement, $Q(t) := \text{Arrivals}(t) - \text{Departures}(t) \rightarrow 2.200 \cdot t - .1000 \cdot t^2$, Q(t) is assigned the value of Arrivals(t) – Departures(t), and this evaluates to $2.2t - 0.10t^2$.

Finally, to assist in quickly identifying the final answer, or answers, for what is being asked in the problem statement, yellow highlighting has been used (which will print as light gray).

[1] www.mathcad.com

Problem 3.1

Determine the elevation and stationing of the low point, PVI and PVT.

$L := 1600$ ft

PVC is at 120 + 00 $\quad sta_{PVC} := 12000 \quad elev_{PVC} := 1500$ (given)

$G_1 := -3.5\% \quad G_2 := 6.5\%$

$A := |-3.5 - 6.5| \qquad A = 10$

$sta_{PVI} := 12000 + \frac{1600}{2} \quad sta_{PVI} = 12800 \quad sta_{PVI} = 128 + 00$

$elev_{PVI} := elev_{PVC} + \left[G_1 \cdot \left(\frac{L}{2}\right)\right] \qquad elev_{PVI} = 1472$ ft

$sta_{PVT} := 12000 + 1600 \quad sta_{PVT} = 13600 \quad sta_{PVT} = 136 + 00$

$Y_f := \frac{A \cdot L}{200} \qquad Y_f = 80$ (Eq. 3.9)

$elev_{PVT} := 1500 + (G_1 \cdot L) + Y_f \qquad elev_{PVT} = 1524$ ft

low point when dy/dx = 2ax + b = 0 (Eq. 3.2)

$a := \frac{G_2 - G_1}{2 \cdot L} \qquad a = 0.000031$ (Eq. 3.6)

$b := G_1 \qquad b = -0.035$ (Eq. 3.3)

$dist_{low} := \frac{-b}{2 \cdot a} \quad dist_{low} = 560$ ft

$sta_{low} := 12000 + 560 \quad sta_{low} = 125{+}60$

offset to low point

$Y_{low} := \frac{A}{200 \cdot L} \cdot dist_{low}^{\ 2} \qquad Y_{low} = 9.8$ ft (Eq. 3.7)

$elev_{low} := 1500 + (G_1 \cdot dist_{low}) + Y_{low} \qquad elev_{low} = 1490.2$ ft

Problem 3.2

Determine the elevation and stationing of the high point, PVC and PVT.

$L := 500$

PVI is at 340 + 00 $sta_{PVI} := 34000$

$elev_{PVI} := 1322$ (given)

$G_1 := 4.0\%$ $G_2 := -2.5\%$

$A := |4.0 + 2.5|$ $A = 6.5$

$sta_{PVC} := sta_{PVI} - \frac{500}{2}$ $sta_{PVC} = 33750$ $sta_{PVC} = 337 + 50$

$elev_{PVC} := elev_{PVI} - \left(G_1 \cdot \frac{L}{2}\right)$ $elev_{PVC} = 1312$ ft

high point when 2ax + b =0

$a := \frac{G_2 - G_1}{2 \cdot L}$ $a = -0.000065$ (Eq. 3.6)

$b := G_1$ $b = 0.04$ (Eq. 3.3)

$dist_{high} := \frac{-b}{2 \cdot a}$ $dist_{high} = 307.692$

$sta_{high} := sta_{PVC} + dist_{high}$ $sta_{high} = 34057.69$ $sta_{high} = 340 + 58$

$Y_{high} := \frac{A}{200 \cdot L} \cdot dist_{high}{}^2$ (Eq. 3.7)

$elev_{high} := elev_{PVC} + \left(G_1 \cdot dist_{high}\right) - Y_{high}$ $elev_{high} = 1318.15$ ft

$sta_{PVT} := sta_{PVI} + \frac{L}{2}$ $sta_{PVT} = 34250$ $sta_{PVT} = 342 + 50$

$Y_{final} := \frac{A \cdot L}{200}$ (Eq. 3.9)

$elev_{PVT} := elev_{PVC} + \left(G_1 \cdot L\right) - Y_{final}$ $elev_{PVT} = 1315.75$ ft

Problem 3.3

Determine the depth of the top of the pipe and the station of the highest point on the curve.

$sta_{PVI} := 11000$ $\quad elev_{PVI} := 1098.4$

$L := 600$ $\quad sta_{pipe} := 11085$ $\quad elev_{pipe} := 1091.6$ $\qquad$ (given)

(elevation is to center of pipe, 4 ft diameter)

$G_1 := 1.2\%$ $\qquad G_2 := -1.08\%$

$sta_{PVC} := 11000 - \frac{L}{2}$ $\qquad sta_{PVC} = 10700$

$elev_{PVC} := elev_{PVI} - \left(G_1 \cdot \frac{L}{2}\right)$ $\qquad elev_{PVC} = 1094.8$

using the parabolic equation, $y = ax^2 + bx + c$

$a := \frac{G_2 - G_1}{2 \cdot L}$ $\qquad a = -1.9 \times 10^{-5}$ $\qquad$ (Eq. 3.6)

$b := G_1$ $\qquad b = 0.01$ $\qquad$ (Eq. 3.3)

$c := elev_{PVC}$ $\qquad c = 1094.8$

elevation of surface over pipe is y(11085-10700), y(385)

$y := a \cdot \left(385^2\right) + b \cdot 385 + c$ $\qquad y = 1096.6$

remember pipe elevation is to center, 4 foot diameter

$depth := 1096.6 - (1091.6 + 2)$ $\qquad depth = 3$ ft

location of high point is when dy/dx=0 $\qquad dy/dx = 2ax + b$

$x := \frac{-b}{2 \cdot a}$ $\qquad x = 315.79$

station of high point = 110 + 15.8

Problem 3.4

Determine if the curve provides sufficient stopping sight distance.

$H_1 := 3.5 \quad H_2 := 2.0$ (assumed)

$A := |1.20 + 1.08| \quad A = 2.28$

$S = SSD\ (60\ mi/h) \quad S := 570$ (Table 3.1)

calculate required curve length for design speed, compare to actual length

Assume S > L

$$L := 2 \cdot S - \frac{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}{A} \quad L = 193.377 \quad ft$$ (Eq. 3.14)

Actual L is greater than calculated minimum L, curve is adequately designed

problem can be done using K-values:

$SSD := 570$ (Table 3.1)

$A := |1.20 + 1.08| \quad A = 2.28$

$L := 600$

solve for K of actual curve, compare to design K for 60 mi/h

$$K := \frac{L}{A} \quad K = 263.158 \quad ft$$ (Eq. 3.17)

from table 3.2, K-value based on SSD for 60 mi/h is 151 ft

since 263 ft > 151 ft, curve is adequately designed

Problem 3.5

Determine the design speed of the curve.

$sta_{PVI} := 11077$ $elev_{PVI} := 947.34$ $sta_{PVC} := 10900$ $elev_{PVC} := 950$ (given)

$sta_{lowpt} := 11050$

solve for initial grade

$$G_1 := \frac{(elev_{PVI} - elev_{PVC})}{(sta_{PVI} - sta_{PVC})} \quad G_1 = -0.015 \quad G_1 = -1.5\%$$

solve for location of low point

$x_L := sta_{lowpt} - sta_{PVC}$ $x_L = 150$ $x_L = |G_1| * K$

$$K := \frac{x_L}{1.5} \quad K = 100 \qquad \text{(Eq. 3.11)}$$

Checking table 3.2, K = 96 is nearest value without going over K = 100; thus, design speed is 50 mi/h.

Problem 3.6

Compute the difference in design curve lengths for 2005 and 2025 designs.

$G_1 := 1$ $\quad G_2 := -2$ $\quad A := |G_2 - G_1|$ $\quad A = 3$ (given)

find required L for 70 mi/h design speed

$K := 247$ (Table 3.2)

$L_{2005} := K \cdot A$ $\quad L_{2005} = 741$ (Eq. 3.17)

$SSD_{2005} := 730$ (Table 3.1)

$V := 70 \cdot \frac{5280}{3600}$ $\quad V = 102.667$

$H_1 := 3$ $\quad H_2 := 1$ $\quad g := 32.2$ $\quad G := 0$ (given)

For 2025 values, a increases by 25% and t_r increases by 20%

$a_{2025} := 11.2 \cdot 1.25$ $\quad a_{2025} = 14$ $\quad t_{r2025} := 2.5 \cdot 1.2$ $\quad t_{r2025} = 3$

Calculate required stopping sight distance in 2025

$$S_{2025} := \frac{V^2}{2 \cdot g \cdot \left[\left(\frac{a_{2025}}{g}\right) - G\right]} + V \cdot t_{r2025} \qquad S_{2025} = 684.444$$ (Eq. 3.12)

Using this distance, calculate required minimum curve length in 2025

$$L_{2025} := \frac{A \cdot S_{2025}{}^2}{200 \cdot \left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$ (Eq. 3.13)

$L_{2025} = 941.435$ $\quad Diff := L_{2025} - L_{2005}$ $\quad Diff = 200.43$ ft

Alternative Solution

$$L_{2002} := \frac{A \cdot SSD_{2005}{}^2}{2158} \qquad L_{2005} = 741$$

$L_{2025} - L_{2005} = 200.435$

Problem 3.7

Determine the height of the driver's eye.

$L := 1200$ $H_2 := 2$ (given)

$K := 84$ (Table 3.2)

calculate A of curve

$A := \frac{L}{K}$ $A = 14.286$ (Eq. 3.10)

solve for H_1, using design SSD for 60 mi/h

$S := 570$

S<L

$$L = \frac{A \cdot S^2}{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$ (Eq. 3.13)

$H_1 = 8.9$ ft

Problem 3.8

Assess the adequacy of this existing curve.

$x := 352 \quad Y_x := 3 \quad L := 800$ (given)

solve for A using known offset

$$Y_x = \frac{A}{200 \cdot L} \cdot x^2 \qquad A := \frac{200 Y_x \cdot L}{x^2}$$ (Eq. 3.7)

$A = 3.874$

Solve for K of existing curve

$$K := \frac{L}{A} \qquad K = 206.507$$ (Eq. 3.10)

From Table 3.2, K for 60 is 151. Since 207 > 151, curve is adequate for 60 mi/h.

problem can also be done using Equation 3.15 for SSD

solve for A using known offset

$$Y_x = \frac{A}{200 \cdot L} \cdot x^2$$ (Eq. 3.7)

$A = 3.874$

(Table 3.1)

$SSD := 570$

Solve for required minimum L, assuming SSD < L

$$L_m := \frac{A \cdot SSD^2}{2158} \qquad L_m = 583.25 \text{ ft}$$ (Eq. 3.15)

Since 800 ft > 583 ft, curve is adequate for 60 mi/h

Determine the stationing and elevation of the PVCs and PVTs.

Problem 3.9

60 mi/h design speed

$sta_{PVCc} = 0{+}00 \qquad elev_{PVCc} := 100 \quad ft$ (given)

$K_c := 151$ (Table 3.2)

$K_s := 136$ (Table 3.3)

$A := |0 - 2| \qquad A = 2$

calculate lengths of crest and sag curves

$L_c := K_c \cdot A \qquad L_c = 302$ (Eq. 3.10)

$L_s := K_s \cdot A \qquad L_s = 272$

Calculate station and elevation of PVT for crest curve,

$sta_{PVIc} = 1{+}51$

$elev_{PVTc} := elev_{PVCc} - \frac{A \cdot L_c}{200} \qquad elev_{PVTc} = 96.98 \quad ft$

$PVT_c := 0 + 302 \qquad PVT_c = 302 \qquad sta_{PVTc} = 3 + 02$

Calculate station and elevation of PVT and PVC for sag curve,

$elev_{PVTs} := elev_{PVCc} - (0.02 \cdot 4000) \qquad elev_{PVTs} = 20 \quad ft$

$PVT_s := \frac{L_c}{2} + 4000 + \frac{L_s}{2} \qquad PVT_s = 4287 \qquad sta_{PVTs} = 42 + 87$

$elev_{PVCs} := elev_{PVTs} + \frac{A \cdot L_s}{200} \qquad elev_{PVCs} = 22.72 \quad ft$

$PVC_s := PVT_s - L_s \qquad PVC_s = 4015 \qquad sta_{PVCs} = 40 + 15$

$PVI_s := PVT_s - \frac{L_s}{2} \qquad PVI_s = 4151 \qquad sta_{PVIs} = 41 + 51$

Problem 3.10

Determine the elevation and stationing of the PVCs and PVTs.

$K_s := 136$ (Table 3.3)

$K_c := 151$ (Table 3.2)

Calculate change in elevation between beginning and end of alignment

$\Delta_{elev} := 0.02 \cdot 4000 \qquad \Delta_{elev} = 80$

Solve for A of both curves

$$\frac{A^2 \cdot K_c}{200} + \frac{A^2 \cdot K_s}{200} + \frac{A \cdot (4000 - K_c \cdot A - K_s \cdot A)}{100} = \Delta_{elev}$$

$A = 2.169$

Calculate lengths of crest and sag curves using common A

$L_c := K_c \cdot A \qquad L_c = 327.479$ (Eq. 3.10)

$L_s := K_s \cdot A \qquad L_s = 294.948$ (Eq. 3.10)

$sta_{PVCc} := 0 + 00 \qquad elev_{PVCc} := 100$ ft (given)

Calculate station and elevation of PVT of sag and crest curves and PVC of sag curve

$sta_{PVTc} := sta_{PVCc} + L_c \qquad sta_{PVTc} = 327.479 \qquad sta_{PVTc} = 3{+}27.48$

$elev_{PVTc} := elev_{PVCc} - \frac{(A \cdot L_c)}{200} \qquad elev_{PVTc} = 96.45$ ft

$elev_{PVCs} := elev_{PVTc} - \frac{A \cdot (4000 - L_c - L_s)}{100} \qquad elev_{PVCs} = 23.2$ ft

$sta_{PVCs} := sta_{PVTc} + (4000 - L_c - L_s) \qquad sta_{PVCs} = 3705.052 \qquad sta_{PVCs} = 37{+}05.05$

$elev_{PVTs} := elev_{PVCs} - \frac{A \cdot L_s}{200} \qquad elev_{PVTs} = 20$ ft $\qquad sta_{PVTs} = 40{+}00$

Problem 3.11

Determine the elevation difference between the PVC and the high point of the curve.

$G_1 := 4.0\%$ (given)

$K := 151$ (Table 3.2)

solve for location of high point on curve

$x_h := K \cdot |4.0| \quad x_h = 604$ (Eq. 3.11)

substituting for L, solve for the offset of the high point

$$Y_x := \frac{A}{200L} \cdot x_h^2$$ (Eq. 3.7)

$L = KA$ (Eq. 3.10)

$$Y_{xh} := \frac{1}{200K} \cdot x_h^2 \qquad Y_{xh} = 12.08 \text{ ft}$$ (Eq. 3.7)

Problem 3.12

Determine the elevation difference between the high point and the PVT.

$G_1 := 3.0 \quad \%$ (given)

$K := 84$ (Table 3.2)

calculate location of high point

$x_h := K \cdot |G_1| \qquad x_h = 252 \ \text{ft}$ (Eq. 3.11)

knowing the station of the high point, calculate the station of the PVC

$PVC := 3337.43 - x_h \qquad PVC = 3085.43$

knowing the station of the PVC, calculate the curve length

$L := 3718.26 - PVC \qquad L = 632.83 \ \text{ft}$

$A := \frac{L}{K} \qquad A = 7.534$ (Eq. 3.10)

calculate the offset of the high point

$Y_x := \frac{A}{200 \cdot L} \cdot x_h^2 \qquad Y_x = 3.78$ (Eq. 3.7)

calculate elevation difference between initial tangent point above high point to initial tangent point above end of curve

$\Delta y_{tan} := (L - x_h) \cdot \frac{G_1}{100} \qquad \Delta y_{tan} = 11.425 \ \text{ft}$

calculate final offset

$Y_f := \frac{A \cdot L}{200} \qquad Y_f = 23.838$ (Eq. 3.9)

elevation difference

$Y_f - \Delta y_{tan} - Y_x = 8.633$ ft

Problem 3.13

Determine the stationing and elevation of the high point on the curve.

$K := 114 \qquad G_1 := 2.5 \qquad G_2 := -1.0$

$A := |G_2 - G_1| \qquad A = 3.5$

(given)

$PVT := 11425$

$point := 11275 \qquad elev_{point} := 240$

calculate curve length

$L := K \cdot A \qquad L = 399$ (Eq. 3.10)

calculate location of PVC

$PVC := PVT - L \qquad PVC = 11026 \qquad sta_{PVC} = 110 + 26$

$x := point - PVC \qquad x = 249$

calculate offset of point above curve

$Y_{point} := \frac{A}{200 \cdot L} \cdot x^2 \qquad Y_{point} = 2.719$ (Eq. 3.7)

$x \cdot \frac{G_1}{100} - Y_{point} = 3.506$

from offset of point, calculate elevation of PVC

$elev_{PVC} := elev_{point} - 3.506 \qquad elev_{PVC} = 236.494$

calculate location of high point

$x_h := K \cdot G_1 \qquad x_h = 285$ (Eq. 3.11)

$Y_h := \frac{A}{200 \cdot L} \cdot x_h^{\,2} \qquad Y_h = 3.562$ (Eq. 3.7)

calculate station and elevation of high point

$elev_{hp} := elev_{PVC} + Y_h \qquad elev_{hp} = 240.06$ ft

$PVC + x_h = 11311 \qquad sta_{hp} = 113 + 11$

Problem 3.14

Determine if the curve is long enough to provide passing sight distance?

$G_1 := 1 \qquad G_2 := -0.5$

$A := |G_1 - G_2| \qquad A = 1.5$ (given)

$sta_{PVC} := 5484 \qquad sta_{PVI} := 5744$

$L := (sta_{PVI} - sta_{PVC}) \cdot 2 \qquad L = 520$

is this curve long enough? calculate actual K-value and compare to required

$K := \frac{L}{A} \qquad K = 346.667$ (Eq. 3.10)

K from Table 3.4 for 55 mi/h is 1407, this curve is not long enough.

problem can also be done using PSD equation (3.25):

(assuming PSD > L)

$L := 520$ (see above)

$A := |1 - (-.5)| \qquad A = 1.5$

$$L = 2 \cdot PSD - \frac{2800}{A}$$ (Eq. 3.25)

$$PSD := \frac{L + \frac{2800}{A}}{2} \qquad PSD = 1193.333 \text{ ft}$$

From Table 3.2, for 55 mi/h, 1985 ft of passing sight distance is required

Therefore, curve is not adequate for 55 mi/h

Problem 3.15

Determine what length of existing highway must be reconstructed.

$K_s := 96$ (Table 3.3)

$K_c := 84$ (Table 3.2)

$\Delta_{elev} := 24$ (given)

Set total of final offsets equal to change in elevation

$$\frac{L_s \cdot A}{200} + \frac{L_c \cdot A}{200} = 24$$ (Eq. 3.9)

substitute in for L_c and L_s and solve for A

$L_s := K_s \cdot A \qquad L_c := K_c \cdot A$ (Eq. 3.10)

$$\frac{K_s \cdot A^2}{200} + \frac{K_c \cdot A^2}{200} = 24$$

$A = 5.164$

Total length of the alignment is the length of both curves plus 100 ft for half of the overpass

$L_t := K_s \cdot A + K_c \cdot A + 100 \qquad L_t = 1029.516$

this length must be cleared on either side of the centerline, so

$L_{total} := 2 \cdot L_t \qquad L_{total} = 2059.03$ ft

Provide the lengths of the curves and constant-grade section.

Problem 3.16

50 mi/h design speed

$K_c := 84$ (Table 3.2)

$K_s := 96$ (Table 3.3)

station of PVC_c = 127 + 00 $sta_{PVCc} := 12700$

station of PVT_s = 162 + 00 $sta_{PVTs} := 16200$

calculate change in elevation between ramp sections

$\Delta_{elev} := 138 - 97 \qquad \Delta_{elev} = 41$

calculate total length of alignment

$L_{total} := sta_{PVTs} - sta_{PVCc} \quad L_{total} = 3500$

set change in elevation equal to sum of offsets and change in elevation of constant grade section

$(Y_{fc} - \Delta Y_c) + \Delta Y_{con} + Y_{fs} = 41$

substitute in for final offsets using Equation 3.9

$$\left(\frac{A_c \cdot L_c}{200} - \frac{4.0 \cdot L_c}{100}\right) + \frac{G_{con} \cdot L_{con}}{100} + \frac{A_s \cdot L_s}{200} = \Delta_{elev}$$

substitute for L_{con} L_c, and L_s

$L = KA$ (Eq. 3.10)

$L_c + L_{con} + L_s = L_{total} \qquad L_{con} = 3500 - K_c{*}A_c - K_s{*}A_s$

$$\frac{K_c \cdot A_c^{\,2}}{200} - \frac{(4.0 \cdot K_c \cdot A_c)}{100} + \frac{G_{con} \cdot \left[L_{total} - (K_c \cdot A_c) - (K_s \cdot A_s)\right]}{100} + \frac{K_s \cdot A_s^{\,2}}{200} = \Delta_{elev}$$

substitute for A_c and A_s

$A_c = |\,4.0 - G_{con}\,| \qquad A_s = |\,G_{con} - 0\,| \qquad A_s = |\,G_{con}\,|$

solve for G_{con}

$$\frac{K_c \cdot (4 + G_{con})^2}{200} - \frac{[4.0 \cdot K_c \cdot (4 + G_{con})]}{100} + \frac{G_{con} \cdot [L_{total} - [K_c \cdot (4 + G_{con})] - K_s \cdot G_{con}]}{100} + \frac{K_s \cdot G_{con}^{\ 2}}{200} = \Delta_{elev}$$

$G_{con} = 1.579$

$A_c := |4.0 - -1.579| \quad A_c = 5.579$

$A_s := |G_{con}| \quad A_s = 1.579$

$L_c := K_c \cdot A_c \quad L_c = 468.64$ ft (Eq. 3.10)

$L_s := K_s \cdot A_s \quad L_s = 151.6$ ft (Eq. 3.10)

$L_{con} := L_{total} - L_c - L_s$

$L_{con} = 2879.77$ ft

Problem 3.17

Determine the lowest grade possible for the constant-grade section that will still complete this alignment.

$PVC_s := 475 \quad elev_{PVCs} := 82$

$PVT_c := 4412 \quad elev_{PVTc} := 131.2$ (given)

calculate total length and change in elevation

$L_{total} := PVT_c - PVC_s \quad L_{total} = 3937$

$elev_{diff} := elev_{PVTc} - elev_{PVCs} \quad elev_{diff} = 49.2$

$K_s := 96$ (Table 3.3)

$K_c := 84$ (Table 3.2)

set total elevation change equal to sum of offsets and changes in elevation from constant grade

$$Y_{fs} + \Delta y_{con} + Y_{fc} = elev_{diff} + \frac{L_s \cdot (|G_{1s}|)}{100} + \frac{L_c \cdot (|G_{2c}|)}{100}$$

$G_{1s} := -1 \qquad G_{2c} := -1$ (given)

$G_{con} = G_{2s} = G_{1c}$

substitue values for final offsets using equation 3.9

$$\frac{A_s \cdot L_s}{200} + \frac{G_{con}}{100} \cdot (L_{total} - L_s - L_c) + \frac{A_c \cdot L_c}{200} = elev_{diff} + \frac{L_s \cdot (|G_{1s}|)}{100} + \frac{L_c \cdot (|G_{2c}|)}{100}$$

substitute in for A_s and A_c

$A_s = |G_{con} - G_{1s}| \qquad A_c = |G_{con} - G_{2c}|$

solve for G_{con}

$$\frac{(|G_{con} - G_{1s}|)^2 \cdot K_s}{200} + \frac{G_{con}}{100} \cdot (L_{total} - |G_{con} - G_{1s}| \cdot K_s - |G_{con} - G_{2c}| \cdot K_c) + \frac{(|G_{con} - G_{2c}|)^2 \cdot K_c}{200} = elev_{diff} + \left[\frac{|G_{con} - G_{1s}| \cdot K_s \cdot (|G_{1s}|)}{100} + \frac{|G_{con} - G_{2c}| \cdot K_c \cdot (|G_{2c}|)}{100}\right]$$

$G_{con} = 1.379 \quad \%$

$$\frac{(G+1)^2 \cdot K_s}{200} + \frac{(G+1)^2 \cdot K_c}{200} + 49.2 = 3937 \cdot \left(\frac{G}{100}\right)$$

$G = 1.38$ %

Problem 3.18

Determine the elevation difference.

$G_{1c} := 3$ $G_{con} := -5$ $G_{2s} := 2$

$K_c := 84$ (Table 3.2)

$K_s := 96$ (Table 3.3)

$A_c := |G_{1c} - G_{con}|$ $A_c = 8$

$A_s := |G_{con} - G_{2s}|$ $A_s = 7$

calculate lengths of crest and sag curve, subtract from total length to find length of constant grade

$L_c := K_c \cdot A_c$ $L_c = 672$ (Eq. 3.10)

$L_s := K_s \cdot A_s$ $L_s = 672$ (Eq. 3.10)

$L_{con} := 3000 - L_s - L_c$ $L_{con} = 1656$

Using final offset equation 3.9, calculate the total elevation difference

$$\left(Y_{fc} - \Delta Y_c\right) + \Delta Y_{con} + \left(Y_{fs} - \Delta Y_s\right) = \text{elevation difference}$$

$Y_{fc} := \frac{A_c \cdot L_c}{200}$ $Y_{fc} = 26.88$ $\Delta Y_c := \frac{G_{1c}}{100} \cdot L_c$ $\Delta Y_c = 20.16$

$Y_{fs} := \frac{A_s \cdot L_s}{200}$ $Y_{fs} = 23.52$ $\Delta Y_s := \frac{G_{2s}}{100} \cdot L_s$ $\Delta Y_s = 13.44$

$\Delta Y_{con} := \frac{|G_{con}|}{100} \cdot L_{con}$ $\Delta Y_{con} = 82.8$

$$\Delta Y := Y_{fc} - \Delta Y_c + \Delta Y_{con} + Y_{fs} - \Delta Y_s$$

$$\left[\frac{A_c \cdot L_c}{200} - \left(\frac{G_{1c}}{100} \cdot L_c\right)\right] + \left(\frac{|G_{con}|}{100} \cdot L_{con}\right) + \frac{A_s \cdot L_s}{200} - \left(\frac{|G_{2s}|}{100} \cdot L_s\right)$$

$\Delta Y = 99.6$ ft

Alternative Solution using parabolic equation directly

$c_c := 100$ arbitrary

$$a_c := \frac{G_{con} - G_{1c}}{2 \cdot \frac{L_c}{100}} \qquad a_c = -0.595$$

$$b_c := G_{1c}$$

$$x_c := \frac{L_c}{100}$$

$$y_c := \left(a_c \cdot x_c^{\,2}\right) + b_c \cdot x_c + c_c \qquad y_c = 93.28$$

$$y_{con} := y_c - \left(\frac{\left|G_{con}\right|}{100} \cdot L_{con}\right) \qquad y_{con} = 10.48$$

$$a_s := \frac{G_{2s} - G_{con}}{2 \cdot \frac{L_s}{100}} \qquad a_s = 0.521$$

$$b_s := G_{con}$$

$$x_s := \frac{L_s}{100}$$

$$y_s := a_s \cdot x_s^{\,2} + b_s \cdot x_s + y_{con} \qquad y_s = 0.4$$

$$\Delta Y := c_c - y_s \qquad \Delta Y = 99.6 \text{ ft}$$

Problem 3.19

Determine the common grade between the sag and crest curves and determine the elevation difference between the PVCs and PVTc.

$G_{1s} := -3.0 \qquad G_{2c} := 2.0 \qquad G_{2s} = G_{1c}$ (given)

$L_{total} := 1275$

$K_c := 84$ (Table 3.2)

$K_s := 96$ (Table 3.3)

$L_{total} = L_s + L_c$

substitute for L_s and L_c

$L = KA \qquad L_{total} = K_s \cdot A_s + K_c \cdot A_c$

substitute for A_s and A_c

$A_s = G - G_{1s} \qquad A_c = G - G_{2c}$

solve for G

$$L_{total} = K_s \cdot (G - G_{1s}) + K_c \cdot (G - G_{2c}) \qquad G := \frac{L_{total} + K \cdot G_{1s} + K \cdot G_{2c}}{K_s + K_c}$$

$G = 6.417$ %

calculate A values, then lengths of crest and sag curves

$A_s := G - G_{1s} \qquad A_s = 9.417$

$A_c := G - G_{2c} \qquad A_c = 4.417$

$L_s := K_s \cdot A_s \qquad L_s = 904$ (Eq. 3.10)

$L_c := K_c \cdot A_c \qquad L_c = 371$ (Eq. 3.10)

using final offset equation 3.9, calculate total elevation difference over alignment

$$elev_{diff} := \frac{A_s \cdot L_s}{200} + \frac{G_{1s}}{100} \cdot L_s + \frac{G_{2c}}{100} \cdot L_c + \frac{A_c \cdot L_c}{200} \qquad elev_{diff} = 31.06 \text{ ft}$$

Problem 3.20

Determine the minimum necessary clearance height of the overpass and the resultant elevation of the bottom of the overpass over the PVI.

For 70 mi/h design speed, $K := 181$ (Table 3.3)

$A := |3 - (-6)|$ $A = 9$ (given)

$L := K \cdot A$ $L = 1629$ (Eq. 3.10)

For 70 mi/h design speed,

$SSD := 730$ (Table 3.1)

Using equation for SSD < L, solve for minimum clearance height

$$L = \frac{A \cdot SSD^2}{800 \cdot (H_c - 5)} \qquad H_c := \frac{A \cdot SSD^2}{800 \cdot L} + 5$$ (Eq. 3.29)

$H_c = 8.68$ ft

This clearance is not enough, use the desirable 16.5 ft of clearance

$H_c := 16.5$ ft

$$Y_m := \frac{A \cdot L}{800} \qquad Y_m = 18.326 \text{ ft}$$ (Eq. 3.8)

clearance at the PVI is the sum of the middle offset and the clearance height provided

$clearance_{PVI} := Y_m + H_c$ $clearance_{PVI} = 34.83$ ft

Problem 3.21

Determine the highest possible value of the final grade in daytime and nighttime conditions.

$PVI := 1000 \quad PVC := 400$

$elev_{PVI} := 138 \quad elev_{overpass} := 162$ (given)

$SSD := 730$ (Table 3.1)

$L := (PVI - PVC) \cdot 2 \quad L = 1200$

for daytime conditions, overpass clearance governs

since L > SSD

$$SSD = \sqrt{\frac{800 \cdot L}{A} \cdot (H_c - 5)}$$ (Eq. 3.29)

substitute in equation for H_c = height of overpass minus height of PVI plus middle offset

$$H_c = elev_{overpass} - \left(elev_{PVI} + \frac{A \cdot L}{800}\right)$$

solve for A

$$SSD = \sqrt{\frac{800 \cdot L}{A} \cdot \left[162 - \left(138 + \frac{A \cdot L}{800}\right) - 5\right]}$$

$A = 9.245$

calculate G_2

$G_1 := -4 \quad G_2 := G_1 + A \quad G_2 = 5.245$

For nighttime conditions, headlights govern

at 70 mi/h $\quad K_s := 181$ (Table 3.3)

check for sufficient length

$L := K_s \cdot A \quad L = 1673.395$ which is greater than 1200 (Eq. 3.10)

Solve for A

$$A := \frac{1200}{K_s} \quad A = 6.63$$ (Eq. 3.10)

$G_2 := A + G_1 \quad G_2 = 2.63$ %

Problem 3.22

Determine how many feet below the railway the curve PVI should be located.

First find clearance based on SSD

$K := 79$ (Table 3.3)

$G_1 := -2 \quad G_2 := 2$ (given)

$A := |G_1 - G_2| \qquad A = 4$

$L := K \cdot A \qquad L = 316$ (Eq. 3.10)

$SSD := 360$ (Table 3.1)

Since SSD >L, use Eq. 3.30 to get H_c

$$L = 2 \cdot SSD - \frac{800 \cdot (H_c - 5)}{A} \qquad H_c := \frac{A \cdot (2 \cdot SSD - L)}{800} + 5 \qquad \text{(Eq. 3.30)}$$

$H_c = 7.02$ ft

7.02 ft is less than the AASHTO desirable clearance height of 16.5 ft, so 16.5 ft will be provided

$H_c := 16.5$

now find necessary elevation of the PVI

$elev_{PVI} = -H_c - Y_m$

$Y_m := \frac{A \cdot L}{800} \qquad Y_m = 1.58$ (Eq. 3.8)

$elev_{PVI} := -H_c - Y_m \qquad elev_{PVI} = -18.08$ ft

Problem 3.23

Determine the highest possible design speed for the curve.

necessary middle ordinate distance is the distance from the centerline minus 1/2 the inside lane

$M_s := 34 - 6 \qquad M_s = 28$ (given)

First try 50 mi/h

$e := .08 \qquad g := 32.2 \qquad V := 50$ (given)

$f_s := .14$ (Table 3.5)

calculate radius to vehicle travel path

$$R_v := \frac{(V \cdot 1.467)^2}{g \cdot (e + f_s)} \qquad R_v = 759.489$$ (Eq. 3.34)

$SSD_{50} := 425$ (Table 3.1)

calculate necessary middle ordinate for 50 mi/h

$$M_{s_{50}} := R_v \cdot \left[1 - \cos\left[\left(\frac{90 \cdot SSD_{50}}{\pi \cdot R_v}\right) \cdot deg\right]\right] \qquad M_{s_{50}} = 29.53 \text{ ft}$$ (Eq. 3.42)

this is larger than 28 ft, so design speed is too high

try 45 mi/h $\qquad V := 45$

$f_s := .145$ (Table 3.5)

calculate radius to vehicle travel path

$$R_v := \frac{(V \cdot 1.467)^2}{g \cdot (e + f_s)} \qquad R_v = 601.516$$ (Eq. 3.34)

$SSD_{45} := 360$ (Table 3.1)

calculate necessary middle ordinate for 45 mi/h

$$M_{s_{45}} := R_v \cdot \left[1 - \cos\left[\left(\frac{90 \cdot SSD_{45}}{\pi \cdot R_v}\right) \cdot deg\right]\right] \qquad M_{s_{45}} = 26.73 \text{ ft}$$ (Eq. 3.42)

this is less than 28 ft, so 45 mi/h is the maximum design speed

Problem 3.24

Determine the station of the PT.

$sta_{PC} := 12410$ $\quad sta_{PI} := 13140$ (given)

$e := 0.06$ $\quad V := 70$ $\quad g := 32.2$

$f_s := 0.10$ (Table 3.5)

calculate radius

$$R_v := \frac{(V \cdot 1.467)^2}{g \cdot (e + f_s)} \qquad R_v = 2046.8$$ (Eq. 3.34)

since road is single-lane, $R := R_v$

$R = 2046.8$

$T := sta_{PI} - sta_{PC}$ $\qquad T = 730$

knowing tangent length and radius, solve for central angle

$$T = R \cdot \tan\left(\frac{\Delta}{2}\right) \qquad \Delta := 2 \cdot \operatorname{atan}\left(\frac{T}{R}\right) \qquad \Delta = 39.258 \deg \qquad \Delta := 39$$ (Eq. 3.36)

calculate length

$$L := \frac{\pi}{180} \cdot R \cdot (\Delta) \qquad L = 1393.2$$ (Eq. 3.39)

$sta_{PT} := sta_{PC} + L$ $\qquad sta_{PT} = 13803.229$ $\qquad sta_{PT} = 138 + 03.23$

Determine the stationing of the PC and PT and determine the safe vehicle speed.

Problem 3.25

$sta_{PI} := 270000 \quad T := 510 \quad \Delta := 40$ (given)

$sta_{PC} := sta_{PI} - T \quad sta_{PC} = 269490 \quad sta_{PC} = 2694{+}90$

$T = R \cdot \tan\left(\frac{\Delta}{2}\right)$ (Eq. 3.36)

$R := \frac{T}{\tan\left(\frac{\Delta}{2} \cdot deg\right)} \quad R = 1401.213$

$L := \frac{\pi}{180} \cdot R \cdot \Delta \quad L = 978.232$ (Eq. 3.39)

$sta_{PT} := sta_{PC} + L \quad sta_{PT} = 270468.232 \quad sta_{PT} = 2704{+}68.23$

Since the road is 4 lanes with 10-ft lanes, the distance from the centerline to R_v is 10 ft + 5 ft

$R_v := R - 10 - 5 \quad R_v = 1386.213$

$e := 0.09 \quad f_s := 0.08 \quad g := 32.2$ (given)

$R_v = \frac{V^2}{g \cdot \left(f_s + \frac{e}{100}\right)}$ (Eq. 3.34)

$V := \sqrt{R_v \cdot g \cdot (f_s + e)} \quad V = 87.11 \quad V := \frac{V}{1.467} \quad V = 59.38$ V is 60 mi/h

---

Problem 3.26

Determine the rate of superelevation required for this curve.

design speed is 70 mi/h

$R_v := 900 \quad V := 70 \quad g := 32.2$ (given)

$f_s := 0.10$ for 70 mi/h (Table 3.5)

$e := \frac{(V \cdot 1.467)^2}{g \cdot R_v} - f_s$ (Eq. 3.34)

$e = 0.264 \ \frac{ft}{ft}$ or 26.4%

Problem 3.27

Determine the superelevation required at the design speed. Also, compute the degree of curve, length of curve, and stationing of the PC annd PT.

$V := 100 \qquad R := 1000 \qquad \Delta := 30$ (given)

$sta_{PI} := 112510 \qquad f_s := 0.20 \qquad g := 32.2$

Since the racetrack is single-lane, $R_v := R \qquad R_v = 1000$

Solve for required superelevation

$$e + f_s = \frac{(V \cdot 1.467)^2}{g \cdot R_v} \cdot (1 - f_s \cdot e)$$ (Eq. 3.34)

$e = 0.413$

solve for degree of curve

$$D := \frac{18000}{\pi \cdot R} \qquad D = 5.73 \text{ degrees}$$ (Eq. 3.35)

use this and Equation 3.39 to solve for length of curve

$$R = \frac{18000}{\pi \cdot D} \qquad L = \frac{\pi}{180} \cdot R \cdot \Delta$$ (Eq. 3.39)

$$L := \frac{100 \cdot \Delta}{D} \qquad L = 523.6 \text{ ft}$$

calculate tangent length

$$T := R \cdot \tan\left(\left(\frac{\Delta}{2} \cdot deg\right)\right) \qquad T = 267.949$$ (Eq. 3.36)

$sta_{PC} := sta_{PI} - T \qquad sta_{PC} = 112242.051 \qquad sta_{PC} = 1122{+}42.05$

$sta_{PT} := sta_{PC} + L \qquad sta_{PT} = 112765.65 \qquad sta_{PT} = 1127{+}65.65$

Problem 3.28

Determine the radius and stationing of the PC and PT.

$sta_{PI} := 25050$ $g := 32.2$ $V := 65$ (given)

$e := 0.08$ $\Delta := 35$

$f_s := 0.11$ (Table 3.5)

calculate radius

$$R_v := \frac{(V \cdot 1.467)^2}{g \cdot (f_s + e)} \qquad R_v = 1486.2 \text{ ft}$$ (Eq. 3.34)

since the road is two-lane with 12-ft lanes

$R := R_v + 6$ $R = 1492.2$ ft

calculate length and tangent length of curve

$$L := \frac{\pi}{180} \cdot R \cdot \Delta \qquad L = 911.534$$ (Eq. 3.39)

$$T := R \cdot \tan\left[\left(\frac{\Delta}{2}\right) \cdot deg\right] \qquad T = 470.489$$ (Eq. 3.36)

$sta_{PC} := sta_{PI} - T$ $sta_{PC} = 24579.511$ $sta_{PC} = 245{+}79.51$

$sta_{PT} := sta_{PC} + L$ $sta_{PT} = 25491.044$ $sta_{PT} = 254{+}91.04$

Problem 3.29

Give the radius, degree of curvature, and length of curve that you would recommend.

$\Delta := 40$ 2 10-ft lanes (given)

for a 70 mph design speed with e restricted to 0.06, $R_v := 2050$ ft (Table 3.5)

$$R := R_v + \frac{5}{2} \qquad R = 2052.5 \text{ ft}$$

$$L := \frac{\pi}{180} \cdot R \cdot \Delta \qquad L = 1432.92 \text{ ft}$$ (Eq. 3.39)

$$D := \frac{18000}{\pi \cdot R} \qquad D = 2.79 \text{ degrees}$$ (Eq. 3.35)

Problem 3.30

Determine the station of the PI and how much distance must be cleared from the center of the lane to give adequate SSD.

$L := 400$ $e := 0.10$ $sta_{PC} := 1735$ (given)

$R_v := 555$ (Table 3.5)

since the ramp is single-lane, $R := R_v$

solve for Δ using length and radius

$L = \frac{\pi}{180} \cdot R \cdot \Delta$ $\Delta := \frac{L \cdot 180}{\pi \cdot R}$ $\Delta = 41.294$ (Eq. 3.36)

$T := R \cdot \tan\left(\frac{\Delta}{2} \cdot deg\right)$ $T = 209.132$ (Eq. 3.39)

$sta_{PI} := sta_{PC} + T$ $sta_{PI} = 1944.132$ $sta_{PI} = 19 + 44.13$

$SSD := 360$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right)$ $M_s = 28.93$ ft (Eq. 3.42)

Problem 3.31

Determine the design speed used.

Since the ramp is a single 12-foot lane, center of roadway is center of traveled path

$\Delta := 90 \quad L := 628 \quad M_s := 19.4$ (given)

using L and Δ, solve for R

$L = \frac{\pi}{180} \cdot R \cdot \Delta \qquad R := \frac{L \cdot 180}{\pi \cdot \Delta} \qquad R = 399.8$ (Eq. 3.39)

$R_v := R \qquad R_v = 399.8$

since Ms and Rv are known, we can use Equation 3.43 to find SSD

$SSD := \frac{\pi \cdot R_v}{90 \cdot deg} \cdot \left(acos\left(\frac{R_v - M_s}{R_v} \right) \right) \qquad SSD = 250.1 \quad ft$ (Eq. 3.43)

from Table 3.1, SSD for 35 mi/h is 250 ft - curve is designed for 35 mi/h

Alternative Solution

since Ms and Rv are known, we can solve Equation 3.42 to find SSD

$M_s = R_v \cdot \left(1 - cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg \right) \right)$ (Eq. 3.42)

$SSD = 250.1 \quad ft$

from Table 3.1, SSD for 35 mi/h is 250 ft - curve is designed for 35 mi/h

Cornering Check

$V := 35 \cdot 1.4667 \qquad V = 51.3$

for 35 mi/h, $f_s := 0.155$ (Table 3.5)

$g := 32.2$

$e := \frac{V^2}{g \cdot R_v} - f_s \qquad e = 0.05$

So this combination of speed, radius, and superelevation is OK

Problem 3.32

Determine a maximum safe speed to the nearest 5 mi/h.

$\Delta := 34 \qquad e := 0.08$ (given)

$PT := 12934 \qquad PC := 12350$

$L := PT - PC \qquad L = 584$

since this is a two-lane road with 12-ft lanes, $M_s := 20.3 + \frac{12}{2} \qquad M_s = 26.3$

$L = \frac{\pi}{180} \cdot R \cdot \Delta \qquad R := \frac{L \cdot 180}{\pi \cdot \Delta} \qquad R = 984.139$ (Eq. 3.39)

$R_v := R - 6 \qquad R_v = 978.139$

First, try 50 mi/h

$SSD := 425$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right) \qquad M_s = 22.99$ (Eq. 3.42)

23 ft is less than 26.3 ft so 50 mi/h is acceptable, but can speed be higher?

try 55 mi/h

$SSD := 495$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right) \qquad M_s = 31.15$ ft (Eq. 3.42)

this value is greater than 26.3 ft, therefore 50 mi/h is the design speed

Check values vs. Table 3.5 - Minimum radius for $e = 0.08$ is 760, R exceeds this value.

Problem 3.33

Determine the distance that must be cleared from the inside edge of the inside lane to provide adequate SSD.

V is 70 mi/h

$SSD := 730$ (Table 3.1)

$R_V := 2050$ (Prob. 3.29)

$$M_S := R_V \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_V} \cdot deg\right)\right)$$ (Eq. 3.42)

$M_S = 32.41$

To inside edge of inside lane (subtracting 1/2 of lane width)

$M_S - 5 = 27.41$ ft

Problem 3.34

Determine the design speed used to design the curve.

$e := 0.06$ (given)

since the road is four-lane with 12-ft lanes, $M_s := 52 - 12 - \frac{12}{2}$ $M_s = 34$ ft

try 60 mi/h

$R_v := 1340$ (Table 3.5)

$SSD := 570$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right)$ $M_s = 30.194$ ft (Eq. 3.42)

this is less than the required distance, try again

try 70 mi/h

$R_v := 2050$ (Table 3.5)

$SSD := 730$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right)$ $M_s = 32.408$ ft (Eq. 3.42)

this is less than the required distance, try again

try 80 mi/h

$R_v := 3060$ (Table 3.5)

$SSD := 910$ (Table 3.1)

$M_s := R_v \cdot \left(1 - \cos\left(\frac{90 \cdot SSD}{\pi \cdot R_v} \cdot deg\right)\right)$ $M_s = 33.765$ ft (Eq. 3.42)

this rounds to 34 ft, therefore the design speed is 80 mi/h

Problem 3.35

Determine the length of the horizontal curve.

$G_1 := 1$ $G_2 := 3$ (given)

$L_s := 420$ $\Delta := 37$ $e := 0.06$

$A_s := |G_2 - G_1|$ $A_s = 2$

$K_s := \frac{L_s}{A_s}$ $K_s = 210$ (Eq. 3.10)

safe design speed is 75 mi/h (K = 206 for 75 mi/h) (Table 3.3)

$R_{v1} := 2510$ or (Table 3.5)

$V := 75$ $f_s := 0.09$

$R_{v2} := \frac{(V \cdot 1.467)^2}{32.2 \cdot (f_s + e)}$ $R_{v2} = 2506.31$ (Eq. 3.34)

since the road is two-lane with 12-ft lanes, $R := R_{v1} + \frac{12}{2}$ $R = 2516$

$L := \frac{\pi}{180} \cdot R \cdot \Delta$ $L = 1624.76$ ft (Eq. 3.39)

Problem 3.36

Determine the station of the PT.

$G_1 := -2.5$ $G_2 := 1.5$ $A := |G_2 - G_1|$ $A = 4$ $K := 206$ (given)

$\Delta := 38$ $e := 0.08$ $PVT := 2510$

$L := K \cdot A$ $L = 824$ (Eq. 3.10)

$PVC := PVT - L$ $PVC = 1686$

$PC := PVC - 292$ $PC = 1394$

$R_V := 2215$ (Table 3.5)

since the road is two-lane, 12-ft lanes

$R := R_V + \frac{12}{2}$ $R = 2221$ ft

$L := \frac{\pi \cdot R \cdot \Delta}{180}$ $L = 1473.02$ ft (Eq. 3.39)

$PT := PC + L$ $PT = 2867.02$ $sta_{PT} = 28 + 67.02$

Problem 3.37

Design the ramp and give the stationing and elevations of the PC, PT, PVCs, and PVTs.

$G_1 := -3 \qquad G_2 := 5$

(given)

$D := 8.0 \qquad \Delta := 90$

using D, solve for R

$R := \frac{18000}{\pi \cdot D} \qquad R = 716.197$ (Eq. 3.35)

From Table 3.5, maximum design speed for this radius is 50 mi/h

$T := R \cdot \tan\left(\frac{\Delta}{2} \cdot deg\right) \qquad T = 716.197$ (Eq. 3.36)

$L := \frac{\pi}{180} \cdot R \cdot \Delta \qquad L = 1125$ (Eq. 3.39)

calculate the elevations of the ramp connections using T and the grades

$elev_{EW} := 150 + T \cdot \frac{G_2}{100} \qquad elev_{EW} = 185.81$

$elev_{NS} := 125 - T \cdot \frac{G_1}{100} \qquad elev_{NS} = 146.486$

$K_s := 96$ (Table 3.3)

$G := \frac{elev_{EW} - elev_{NS}}{L} \cdot 100 \qquad G = 3.495$

calculate the lengths of the two sag curves using Equation 3.10

$A_1 := |G_1 - G| \qquad A_1 = 6.495 \qquad A_2 := |G - G_2| \qquad A_2 = 1.505$

$L_1 := K_s \cdot A_1 \qquad L_1 = 623.564 \qquad L_2 := K_s \cdot A_2 \qquad L_2 = 144.436$

calculate the length of the connecting grade

$L_{con} := L - \frac{(L_1 + L_2)}{2} \qquad L_{con} = 741$ ft finally, calculate the station and elevation of all PVCs, PVTs, PCs, and PTs

$PC := 1500$ $15 + 00$		(given)
$PT := PC + L$	$PT = 2625$	$26 + 25$
$PVC_s := PC - \frac{L_1}{2}$	$PVC_s = 1188.218$	$11 + 88.2$
$PVT_s := PC + \frac{L_1}{2}$	$PVT_s = 1811.782$	$18 + 11.8$
$PVC_{s2} := PVT_s + L_{con}$	$PVC_{s2} = 2552.782$	$25 + 52.8$
$PVT_{s2} := PT + \frac{L_2}{2}$	$PVT_{s2} = 2697.218$	$26 + 97.2$

$elev_{PC} := elev_{NS}$	$elev_{PC} = 146.486$
$elev_{PT} := elev_{EW}$	$elev_{PT} = 185.81$
$elev_{PVCs} := elev_{PC} - \frac{L_1}{2} \cdot \frac{G_1}{100}$	$elev_{PVCs} = 155.839$
$elev_{PVTs} := elev_{PC} + \frac{L_1}{2} \cdot \frac{G}{100}$	$elev_{PVTs} = 157.384$
$elev_{PVCs2} := elev_{PVTs} + L_{con} \cdot \frac{G}{100}$	$elev_{PVCs2} = 183.286$
$elev_{PVTs2} := elev_{PT} + \frac{L_2}{2} \cdot \frac{G_2}{100}$	$elev_{PVTs2} = 189.421$

Multiple Choice Problems

Determine the elevation of the lowest point of the curve.

Problem 3.38

$G_1 := -4.0$ $G_2 := 2.5$ $L := 4$ stations (given)

$c := 500$ ft

stationing and elevation for lowest point on the curve

$\frac{dy}{dx} := (2a \cdot x + b) = 0$ (Eq. 3.1)

$b := -4.0$ (Eq. 3.3)

$a := \frac{G_2 - G_1}{2 \cdot L}$ $a = 0.813$ (Eq. 3.6)

$x := \frac{-b}{2 \cdot a}$ $x = 2.462$ stations (Eq. 3.1)

Lowest Point stationing: (100 + 00) + (2 + 46) = 102 + 46

Lowest Point elevation: $y := a \cdot (x^2) + b \cdot x + c$ $y = 495.077$ ft (Eq. 3.1)

Alternative Answers:

1) Miscalculation $y := 492.043$ ft

2) Miscalculate "a" $a := \frac{G_1 - G_2}{2 \cdot L}$ $a = -0.813$ Station = 102 + 46

$y := a \cdot (x^2) + b \cdot x + c$ $y = 485.231$ ft

3) Assume lowest point at L/2 Station = 102 + 00

$x := 2$ $y := a \cdot (x^2) + b \cdot x + c$ $y = 495.25$ ft

Determine the station of *PT.*

Problem 3.39

$T := 1200$ ft $\qquad \Delta := \dfrac{0.5211 \cdot 180}{\pi}$ (given)

Calculate radius

$$R := \frac{T}{\tan_{[mc]}\left[\left(\frac{\Delta}{2}\right)\cdot deg\right]} \qquad R = 4500.95 \text{ ft}$$ (Eq 3.36)

Solve for length of curve

$$L := \frac{\pi}{180}\cdot R\cdot \Delta \qquad L = 2345.44 \text{ ft}$$ (Eq 3.39)

Calculate stationing of PT

stationing PC = 145 + 00 minus 12+00 = 133 + 00

stationing PT = stationing PC + L

= 133 + 00 plus 23 + 45.43 = 156 + 45.43

Alternative Answers:

1) Add length of curve to stationing PI

stationing PT = 145 + 000 plus 23 + 45.43 = 168 + 45.43

2) Use radians instead of degrees

$$R := \frac{T}{\tan\left(\frac{0.5211}{2}\right)} \qquad R = 4500.95 \text{ ft}$$

$$L := \frac{\pi}{180}\cdot R\cdot 0.5211 \qquad L = 40.94 \text{ ft}$$

stationing PT = 133 + 00 plus 40 + 94 = 173 + 94

3) add half of length to stationing PI

stationong PT = 145 + 00 plus 11 +72.72 = 156 + 72.72

Determine the offset.

Problem 3.40

$G_1 := 5.5\ \%$ $G_2 := 2.5\ \%$ $x := 750\ ft$ $L := 1600\ ft$ (given)

determine the absolute value of the difference of grades

$A := |G_1 - G_2|$ $A = 3$

determine offset at 750 feet from the PVC

$Y := \frac{A}{200 \cdot L} \cdot x^2$ $Y = 5.273\ ft$ (Eq 3.7)

Alternative Answers:

1) Use Y_m equation.

$Y_m := \frac{A \cdot L}{800}$ $Y_m = 6\ ft$ (Eq 3.8)

2) Use Y_f equation.

$Y_f := \frac{A \cdot L}{200}$ $Y_f = 24\ ft$ (Eq 3.9)

3) Use 0.055 and 0.025 for grades.

$G_1 := 0.055$ $G_2 := 0.025$

$A := |G_1 - G_2|$ $A = 0.03$

$Y := \frac{A}{200 \cdot L} \cdot x^2$ $Y = 0.053\ ft$

Determine the minimum length of curve.

Problem 3.41

$V := 65 \cdot \left(\frac{5280}{3600}\right)$ $\frac{ft}{s}$ $G_1 := 1.5$ $G_2 := -2.0$ (given)

ignoring the effect of grades

using Table 3.1, SSD for 65 mi/h would be 645 ft (assuming L > SSD)

$SSD := 645$ ft (Table 3.1)

$A := |G_1 - G_2|$ $A = 3.50$

$L_m := \frac{A \cdot SSD^2}{2158}$ $L_m = 674.74$ ft (Eq. 3.15)

$674.74 > 645$

Alternative Answers

1) assume L < SSD

$L_m := 2 \cdot SSD - \frac{2158}{A}$ $L_m = 673.43$ ft (Eq. 3.16)

2) Misinterpret chart for 70 mi/h

$SSD := 730$ $L_m := \frac{A \cdot SSD^2}{2158}$ $L_m = 864.30$ ft

3) Assume SSD is equivalent to L_m

$SSD := 645$ $L_m := SSD$ therefore $L_m = 645.00$ ft

Determine the stopping sight distance.

Problem 3.42

$V_1 := 35 \cdot \frac{5280}{3600} \ \frac{ft}{s}$ $G := \frac{3}{100}$ (given)

$a := 11.2 \ \frac{ft}{s^2}$ $g := 32.2 \ \frac{ft}{s^2}$ $t_r := 2.5 \ s$ (assumed)

Determine stopping sight distance

$$SSD := \frac{V_1^{\ 2}}{2 \cdot g \cdot \left(\frac{a}{g} - G\right)} + V_1 \cdot t_r$$ $SSD = 257.08 \ ft$ (Eq 3.12)

Alternative Answers:

1) Assume grade is positive (uphill)

$$SSD := \frac{V_1^{\ 2}}{2 \cdot g \cdot \left(\frac{a}{g} + G\right)} + V_1 \cdot t_r$$ $SSD = 236.63 \ ft$

2) Use g = 9.81 m/s^2 instead of g = 32.2 ft/s^2

$g := 9.81 \ \frac{m}{s^2}$

$$SSD := \frac{V_1^{\ 2}}{2 \cdot g \cdot \left(\frac{a}{g} - G\right)} + V_1 \cdot t_r$$ $SSD = 249.15 \ ft$

3) Miscalculation

$SSD := 254.23 \ ft$

Determine the minimum length of the vertical curve.

Problem 3.43

$G_1 := 4.0$ $G_2 := -2.0$ $H_1 := 6.0$ ft $H_2 := 4.0$ ft

(given)

$S := 450$ ft $V := 40 \cdot \frac{5280}{3600} \frac{ft}{s}$

Calculate the minim length of vertical curve

$A := |G_1 - G_2|$

$$L_m := 2 \cdot S - \frac{200 \cdot \left(\sqrt{H_1} + \sqrt{H_2}\right)^2}{A}$$

$L_m = 240.07$ ft

(Eq 3.14)

Alternative Answers:

1) Use equation 3.13

$$L_m := \frac{A \cdot S^2}{200 \cdot \left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$

$L_m = 306.85$ ft

(Eq 3.13)

2) Use AASHTO guidelines for heights and equation 3.13

$H_1 := 3.5$ ft $H_2 := 2.0$ ft

$$L_m := \frac{A \cdot S^2}{200 \cdot \left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$

$L_m = 562.94$ ft

3) Solve for S and not L_m

$L_m := 450$ ft

$$S := \frac{L_m + 200 \cdot \left(\sqrt{H_1} + \sqrt{H_2}\right)^2}{2}$$

$S = 1304.15$ ft