5 Vertical Alignment

5.1 Objectives

1. Understand basic philosophies in establishing a vertical alignment
2. Apply criteria for selection of grades
3. Design a vertical Curve

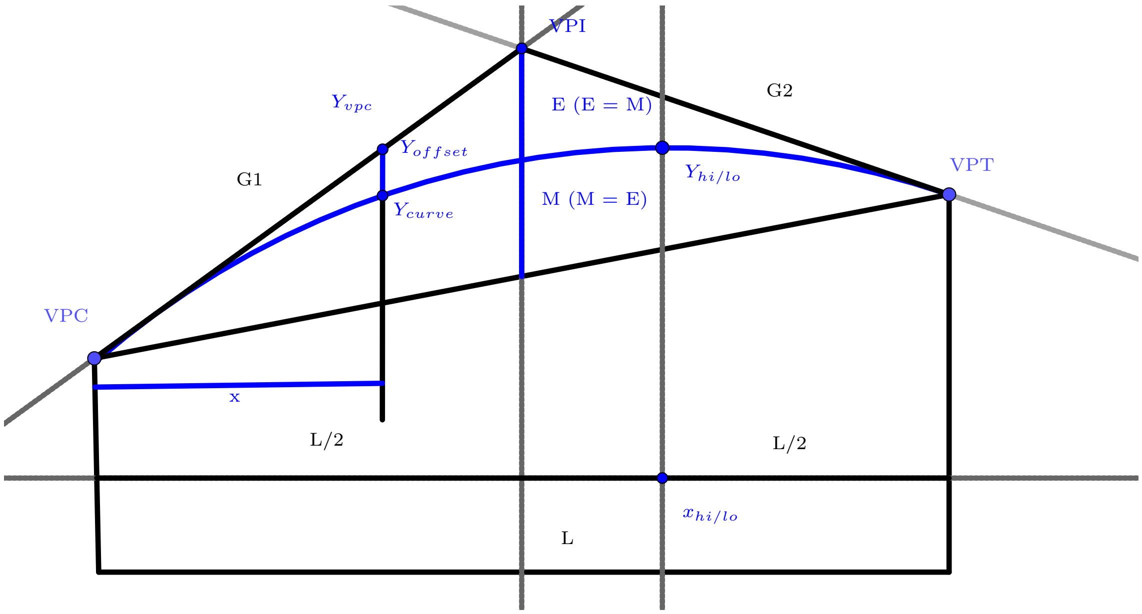
5.2 philosophies

1. conform to the existing terrain (within constraints of max grade and min lengths of vertical curves)
2. to minimize impacts (balance earthwork)
3. coordinate horizontal and vertical alignments (HC and VC)
   (a) avoid steep (near the max) grades and sharp (near min radius) horizontal curve
   (b) avoid placing the start of HC in the middle of VC; VC either at HC tangents or at HC vurves
   (c) avoid placing the start of HC at the bottom of a steep VC

5.3 maximum grades

1. Steepness and length heavily impacts heavy vehicles.
2. max grade design criteria is related with: design speed, the functional classification, and terrain
3. max grades: by AASHTO
   (a) freeway: 3-6%, +3.00% 70mph; max +4.00% for upgrade, max -5.00% for downgrade
   (b) arterials: +3.00% 60mph; up to +8.00% 40mph at mountainous
   (c) collectors: +4.00% 70mph; up to +14.00% 20 mph, mountainous
   (d) locals: up to +17.00% in mountainous terrain
4. min grades:
   (a) urban design(curb and gutter): an appropriate min grade is 0.5%, but grade of .30% ...
   (b) rural deisgn(shoulder and ditches): ... cross-slope is adaquate ...

5.4 Vertical Curve



If G_1 and G_2 are in slope, e.g. +0.02, x and L must in feet

$A = G_2 - G_1$

A: total change in grade, if negative, the curve is below the tangent

G_n: grade, like -0.08

$$Y_{offset} = x^2 \frac{A}{2L} = x^2 \frac{G_2 - G_1}{2L}$$

Y_{offset} : vertical offset from a tangent to a parabola, maybe negative!!!

$$Y_{tan} = Y_{vpc} + G_1 x$$

Y_{tan} : tangent elevation

$$Y_{curve} = Y_{vpc} + G_1 x + \frac{A}{2L} x^2$$

Y_{curve} : curve elevation

$$Y_{tan} = Y_{offset} + Y_{curve}$$

$$x_{hi/lo} = L \frac{G_1}{G_1 - G_2}$$

$x_{hi/lo}$: the highest/lowest point

5.5 stopping/passing sight distance on crest curves

$A = G_2 - G_1$

***SSD/PSD* minimum length of crest curve:**

$$L = \frac{|A|S^2}{200(\sqrt{h_1} + \sqrt{h_2})^2} \text{ when } S \leq L$$

$$L = 2S - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{|A|} \text{ when } S \geq L$$

stopping: $h_1 = 3.5ft$, $h_2 = 2.0ft$

passing: $h_1 = 3.5ft$, $h_2 = 3.5ft$

***SSD* minimum length of crest curve:**

$$L_{SSD} = \frac{|A|S^2}{2158} \text{ when } S \leq L$$

$$L_{SSD} = 2S - \frac{2158}{|A|} \text{ when } S \geq L$$

A: in unit %, e.g. 3, the grade change of VC

L: the minimum length of the vertical curve ??? the arc length or the horizontal segment length???

S: stop sight distance, related with speed, reaction time, and coefficient of friction

h_1 : 3.5 feet, the driver eye height

h_2 : **2.0 feet, the object height**

5.6 sag sight distance

TODO diagram???

minimum length of sag curve

$$L = \frac{|A|S^2}{200(h + S \cdot tan\beta)} \text{ when } S \leq L$$

$$L = 2S - \frac{200(h + S \cdot tan\beta)}{|A|} \text{ when } S \geq L$$

$$L = \frac{|A|S^2}{400 + 3.5S} \text{ when } S \leq L$$

$$L = 2S - \frac{400 + 3.5S}{|A|} \text{ when } S \geq L$$

A: in unit %, e.g. 3, the grade change of VC

L: the horizontal length of sag curve

S: sag sight distance

h: 2 feet, the headlamp height

β : 1 degree, the headlamp beam angle

5.7 Vertical curve design - AASHTO elevation table - K^a factor

Another approach to determining curve length!

$L = K \cdot A$

L: in feet, curve length, minimum length for a given design speed

A: in unit %, change in grade, $A = G_2 - G_1$

K: rate of vertical curvature, K = required ft of curve length per 1% net change in grade

K: refter to K tables for a given design speed

K table for crest VC

K table for sag VC

Design Speed (mph)	**Stopping Sight Distance (ft)**	**Rate of Vertical Curvature, K^a**	
		Calculated	**Design**
15	80	3.0	3
20	115	6.1	7
25	155	11.1	12
30	200	18.5	19
35	250	29.0	29
40	305	43.1	44
45	360	60.1	61
50	425	83.7	84
55	495	113.5	114
60	570	150.6	151
65	645	192.8	193
70	730	246.9	247
75	820	311.6	312
80	910	383.7	384

Table 1: K Table for Crest Vertical Curve - U.S. Customary

Design Speed (mph)	**Stopping Sight Distance (ft)**	**Rate of Vertical Curvature, K^a**	
		Calculated	**Design**
15	80	9.4	10
20	115	16.5	17
25	155	25.5	26
30	200	36.4	37
35	250	49.0	49
40	305	63.4	64
45	360	78.1	79
50	425	95.7	96
55	495	114.9	115
60	570	135.7	136
65	645	156.5	157
70	730	180.3	181
75	820	205.6	206
80	910	231.0	231

Table 2: K Table for Sag Vertical Curve - U.S. Customary

5.8 K table for Crest VC, for a given design speed

5.9 K table for Sag VC, for a given design speed

5.10 elevation in highway design

1. elevations are typically computed at the PVC, PVT, each 100-ft station, and the high or low point
2. procedure:
   (a) calc A
   (b) determine station and elevation of PVI
   (c) Calculate the minimum length of the curve joining the tangents,
   (d) - typicallly using SSD and K factor
   (e) - A vertical curve length can be selected first and then checked to verify that K (based on L/A) $\geq$ Kmin

5.11 Terms

gradient: slope rate grade: e.g. +4.00% a upward slope; -3.00% a downward slope

5.12 Rules

5.13 Formulas

5.14 Reference