Course Logistics

- HW3 due today
- Feedback form online
- Midterms distributed
- HW4 available tomorrow
- No class Wednesday
- Midterm 2, 11/25

Geometric Design

CEE 320
Anne Goodchild

Introduction

- http://www.youtube.com/watch?v=U_JF_xPhpKA

Outline

1. Concepts
2. Vertical Alignment
   a. Fundamentals
   b. Crest Vertical Curves
   c. Sag Vertical Curves
   d. Examples
3. Horizontal Alignment
   a. Fundamentals
   b. Superelevation
4. Other Stuff

Draw a roadway

- Street view
- Arial view
- Side view

Identify a point on that roadway

- Address (relative system)
- Milepost system
  - Linear referencing system
- Grid system
  - Longitude and latitude
  - Altitude

Highway Alignment

- Simplify from x-y plane to a linear reference system (distance along that roadway)
- Assume travel is along some horizontal plane, not the surface of the earth
- Elevation from this horizontal plane

Concepts

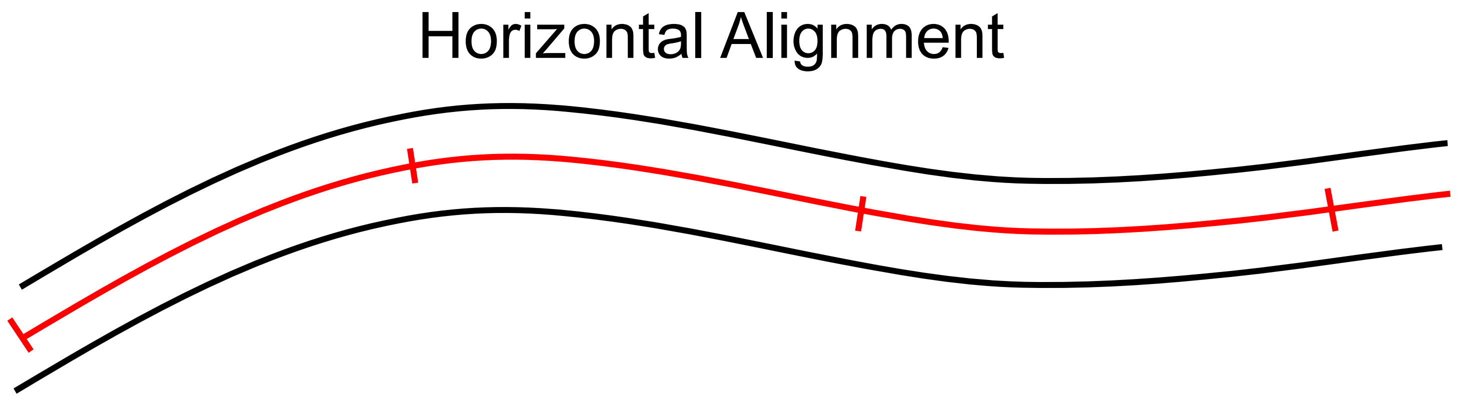
- **Alignment is a 3D problem broken down into two 2D problems**
  - **Horizontal Alignment (arial or plan view)**
  - **Vertical Alignment (side or profile view)**

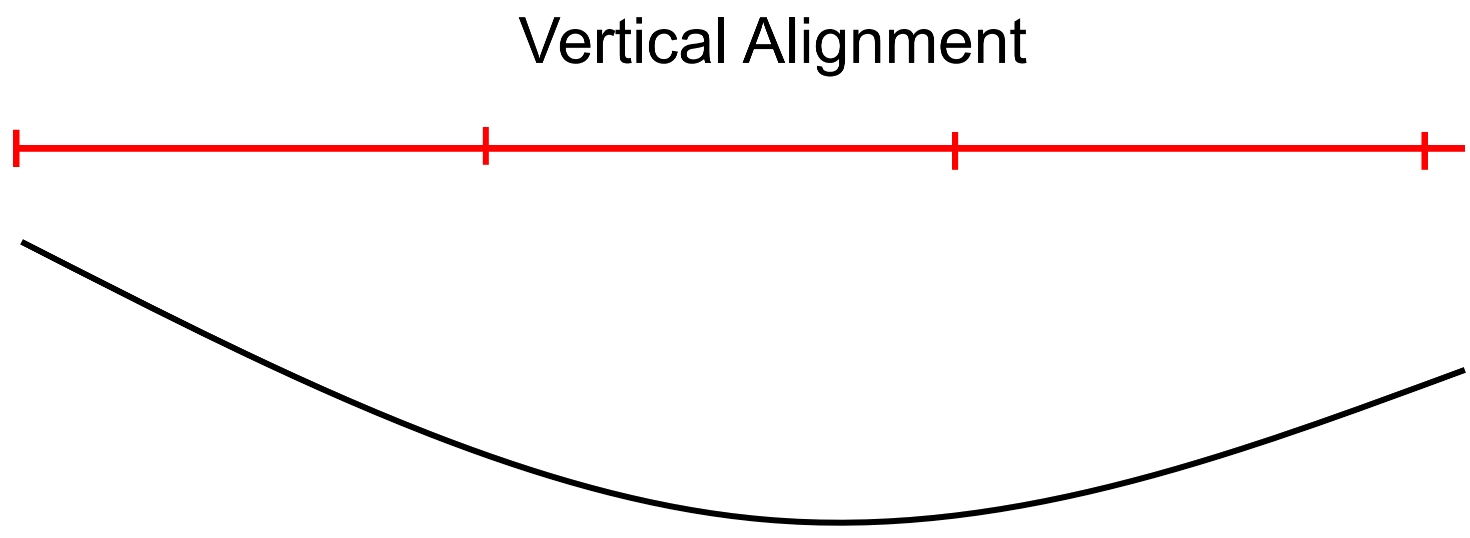
Piilani Highway on Maui

Concepts

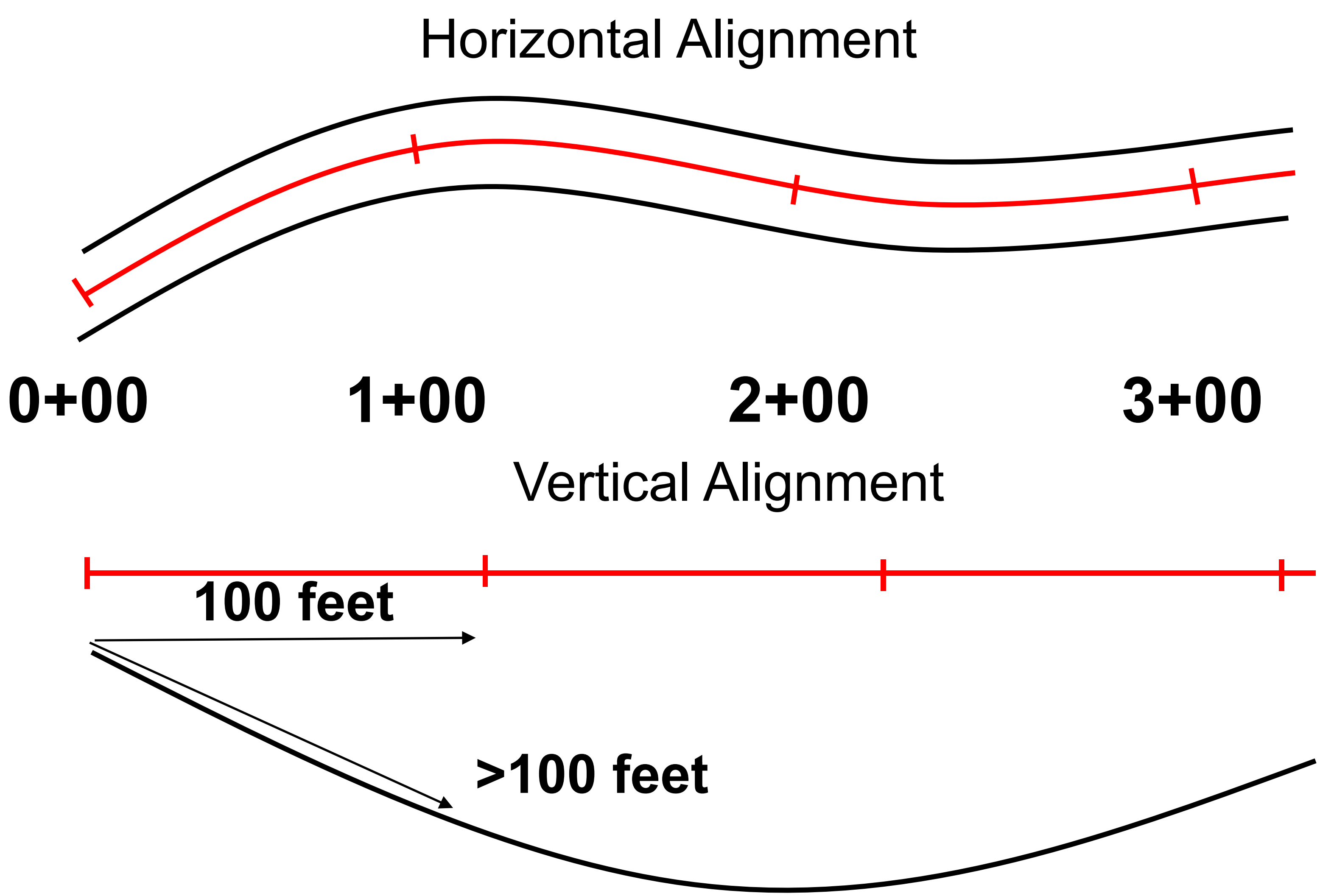
- Stationing is a measurement system for the design problem
  - Along horizontal alignment
  - One station is 100 feet along the horizontal plane
  - 12+00 = 1,200 ft.
  - The point of origin or reference is at station 0+00

Stationing – Linear Reference System





Stationing – Linear Reference System



Questions

- How are mileposts or mile markers different from stations?
- Could two distinct pieces of roadway have the same station?
- Why stationing?

Kawazu-Nanadaru Loop Bridge

Alignment

- Main concern is the transition between two constant slopes
- Vertical alignment this means transition between two grades
- Horizontal alignment this means transition between two directions

Existing tools

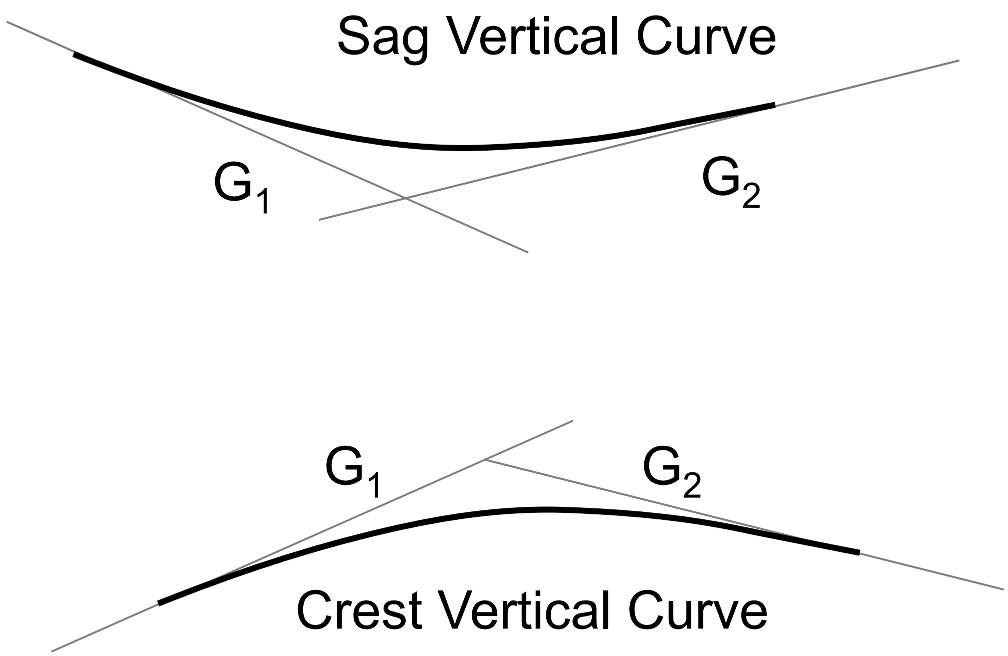
- **Autodesk AutoCAD Civil 3D**
- **http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=8777490**

Vertical Alignment

Vertical Alignment

- Objective: Determine elevation to ensure
  - Proper drainage
  - Acceptable level of safety
    - – Can a driver see far enough ahead to stop?
    - – Do the driver’s light illuminate the roadway far enough ahead to stop?
    - – Can the vehicle be controlled during the transition under typical conditions?

Vertical Alignment



G is roadway grade in ft/ft.
G=0.05 is a 5% grade.

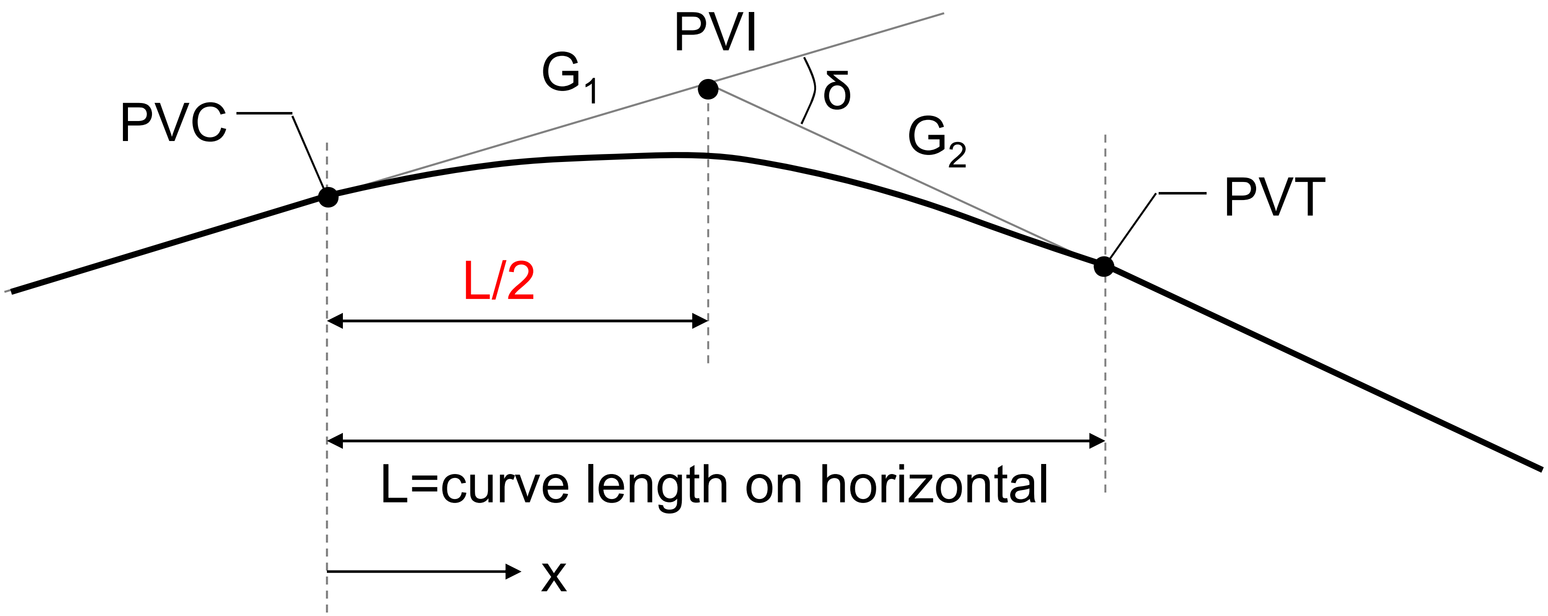
Vertical Curve Fundamentals

- **Assume parabolic function**
  - **Constant rate of change of slope**

$$y = ax^2 + bx + c$$

- **y is the roadway elevation x stations (or feet) from the beginning of the curve**

Vertical Curve Fundamentals

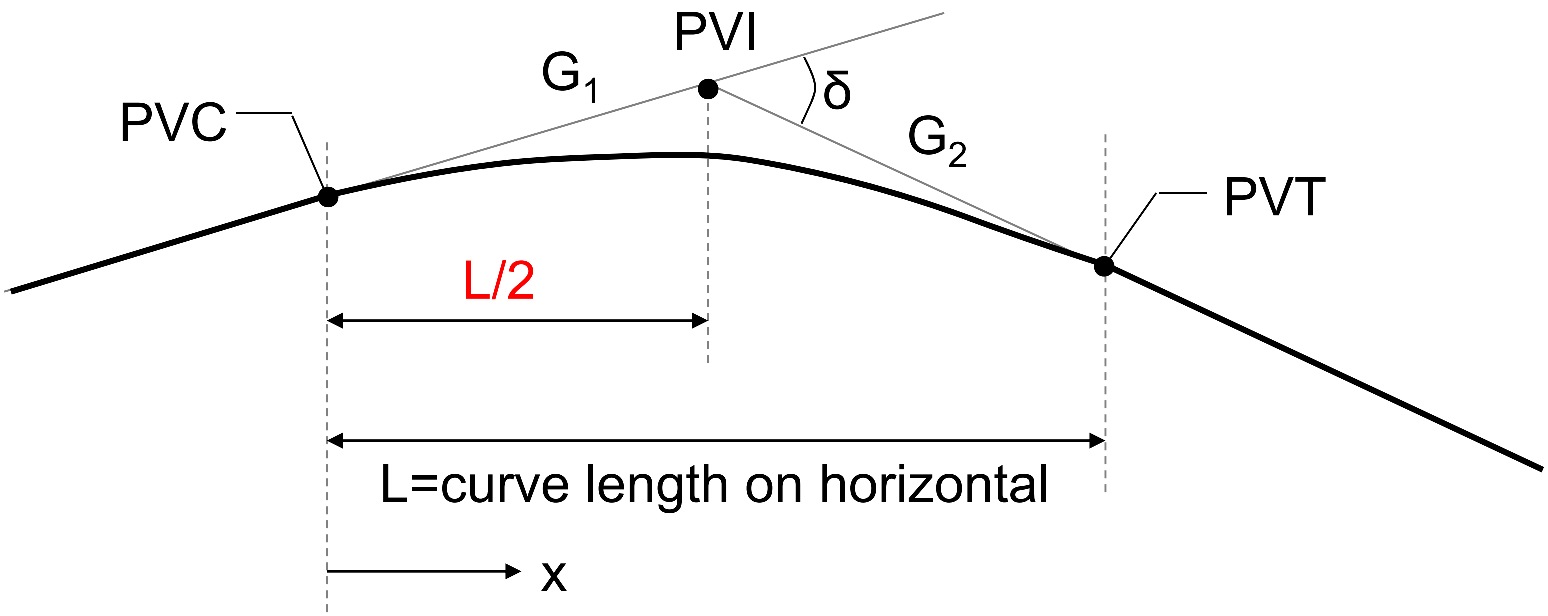


$$y = ax^2 + bx + c$$

Choose Either:

- G_1, G_2 in decimal form, L in feet
- G_1, G_2 in percent, L in stations

Vertical Curve Fundamentals



PVC and PVT may have some elevation difference

Rate of change **of grade is constant, not grade itself**

Maximum height of the <u>curve</u> is not necessarily at L/2

$$y = ax^2 + bx + c$$

At the PVC: $x = 0$

$$y = ax^2 + bx + c$$

$$\frac{dY}{dx} =$$

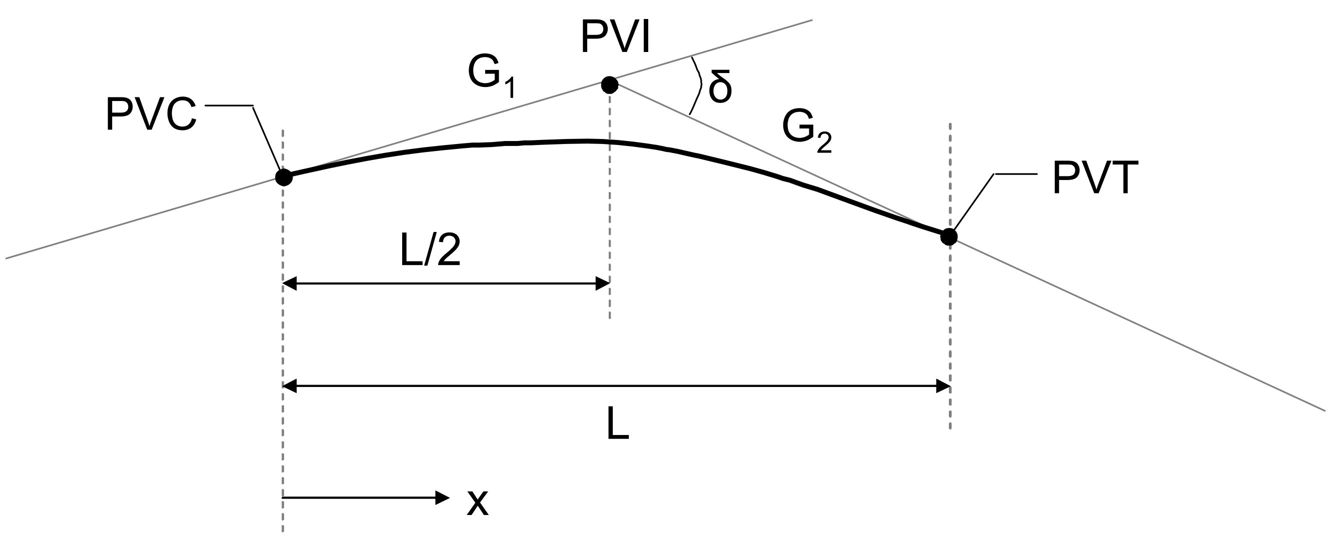
$$\text{At the PVC}: \; x = 0$$

Relationships

Choose Either:

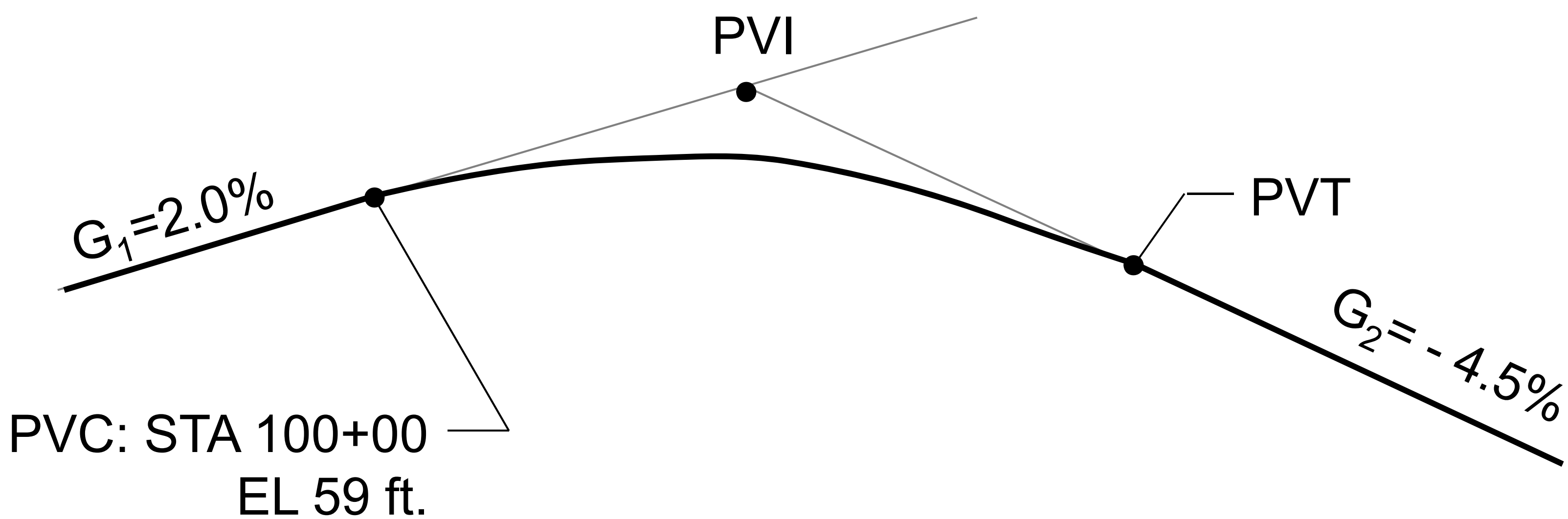
- G_1, G_2 in decimal form, L in feet
- G_1, G_2 in percent, L in stations

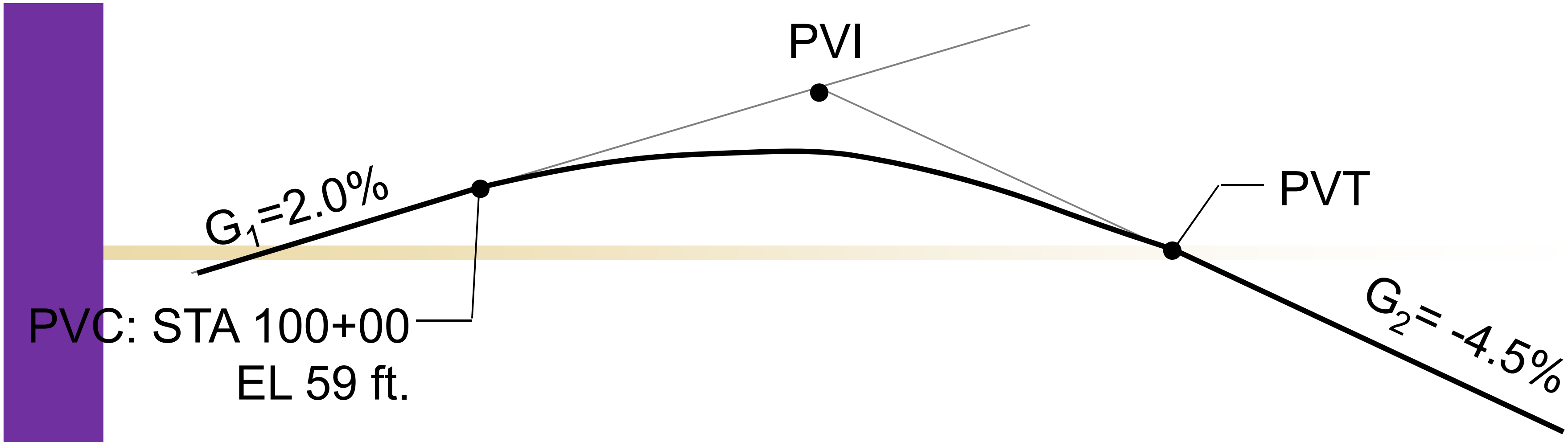
$$\text{Anywhere:} \quad \frac{d^2Y}{dx^2} = 2a = \frac{G_2 - G_1}{L} \Rightarrow a = \frac{G_2 - G_1}{2L}$$



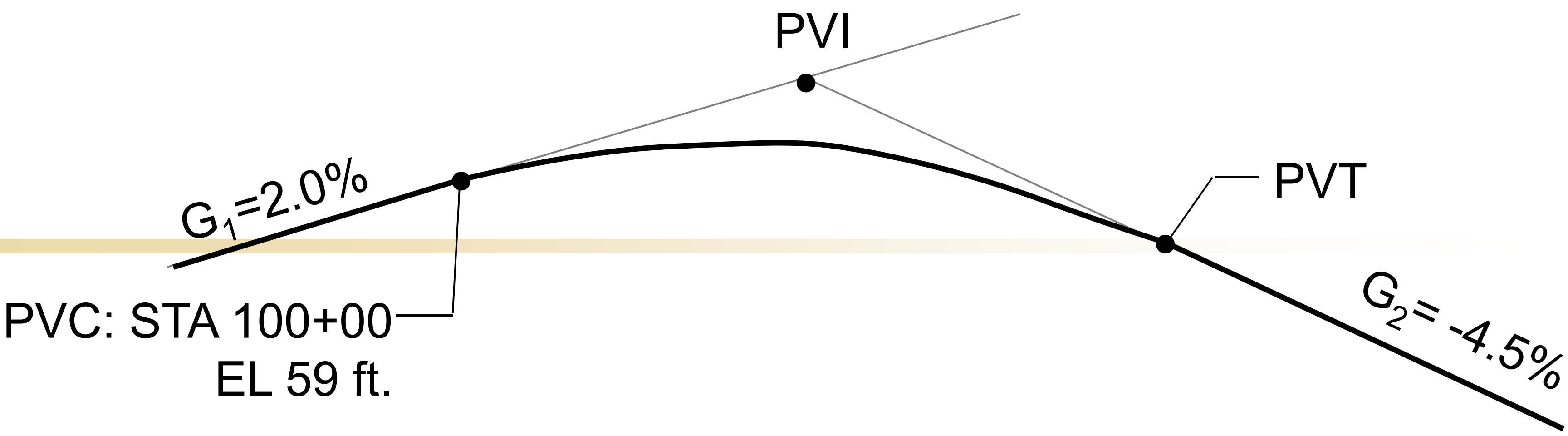
Example

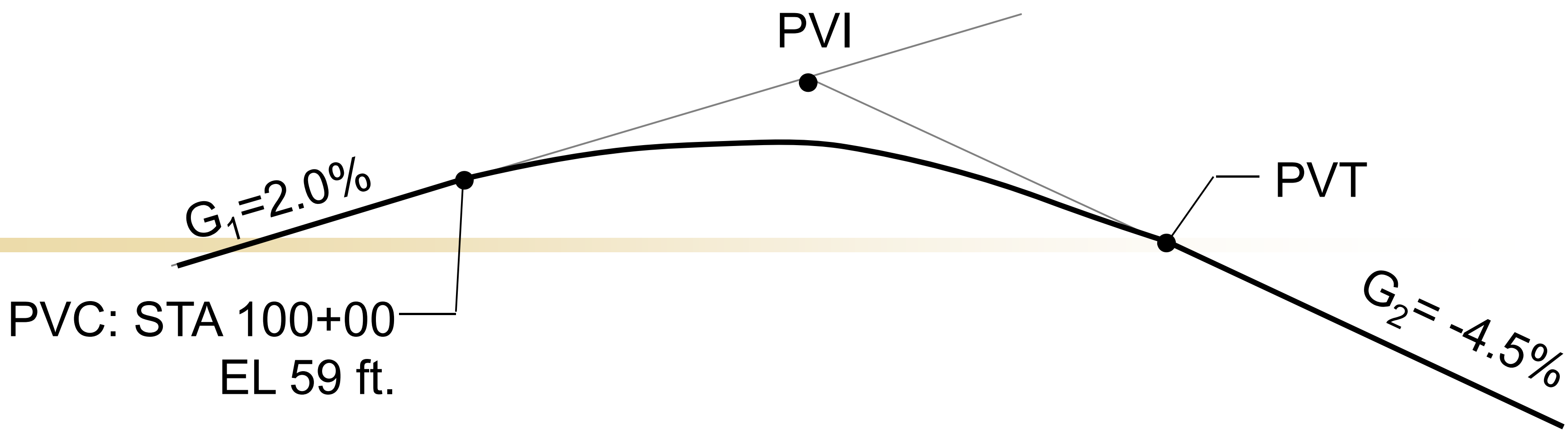
A 400 ft. equal tangent crest vertical curve has a PVC station of 100+00 at 59 ft. elevation. The initial grade is 2.0 percent and the final grade is -4.5 percent. Determine the elevation and stationing of PVT, and the high point of the curve.





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

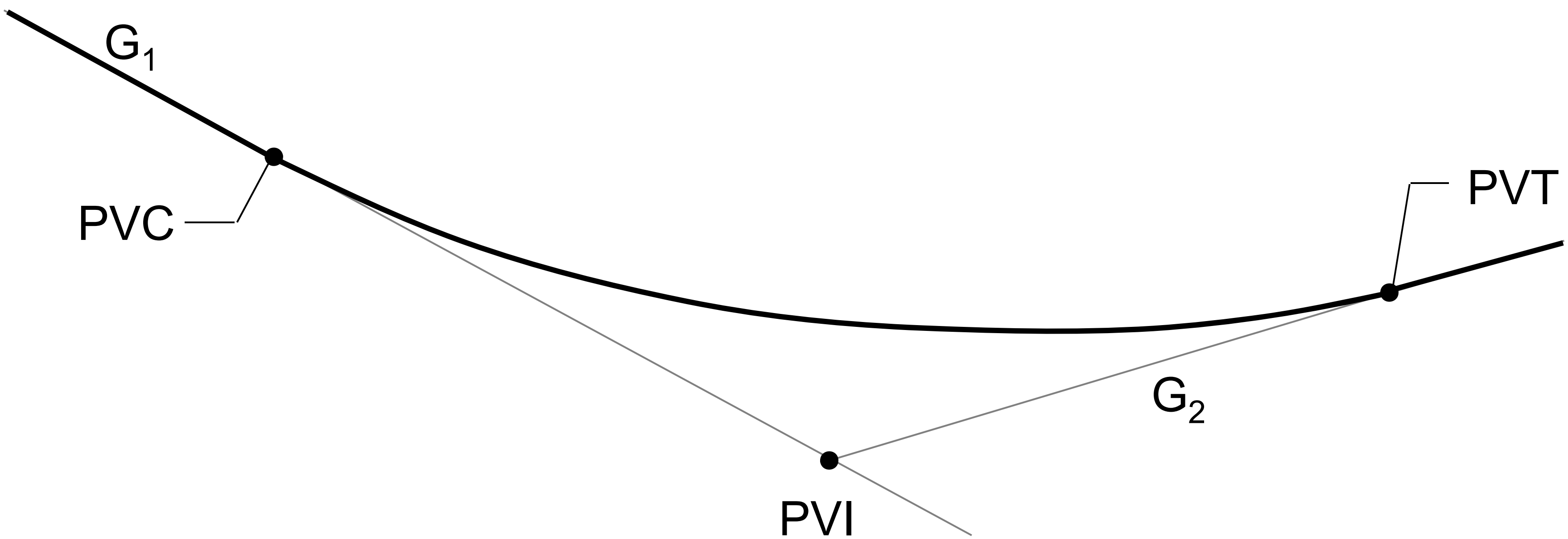

PVI
PVT
G1=2.0%
G2= -4.5%
PVC: STA 100+00
EL 59 ft.



PVI
PVT
G_1=2.0%
G_2= -4.5%
PVC: STA 100+00
EL 59 ft.

Other Properties

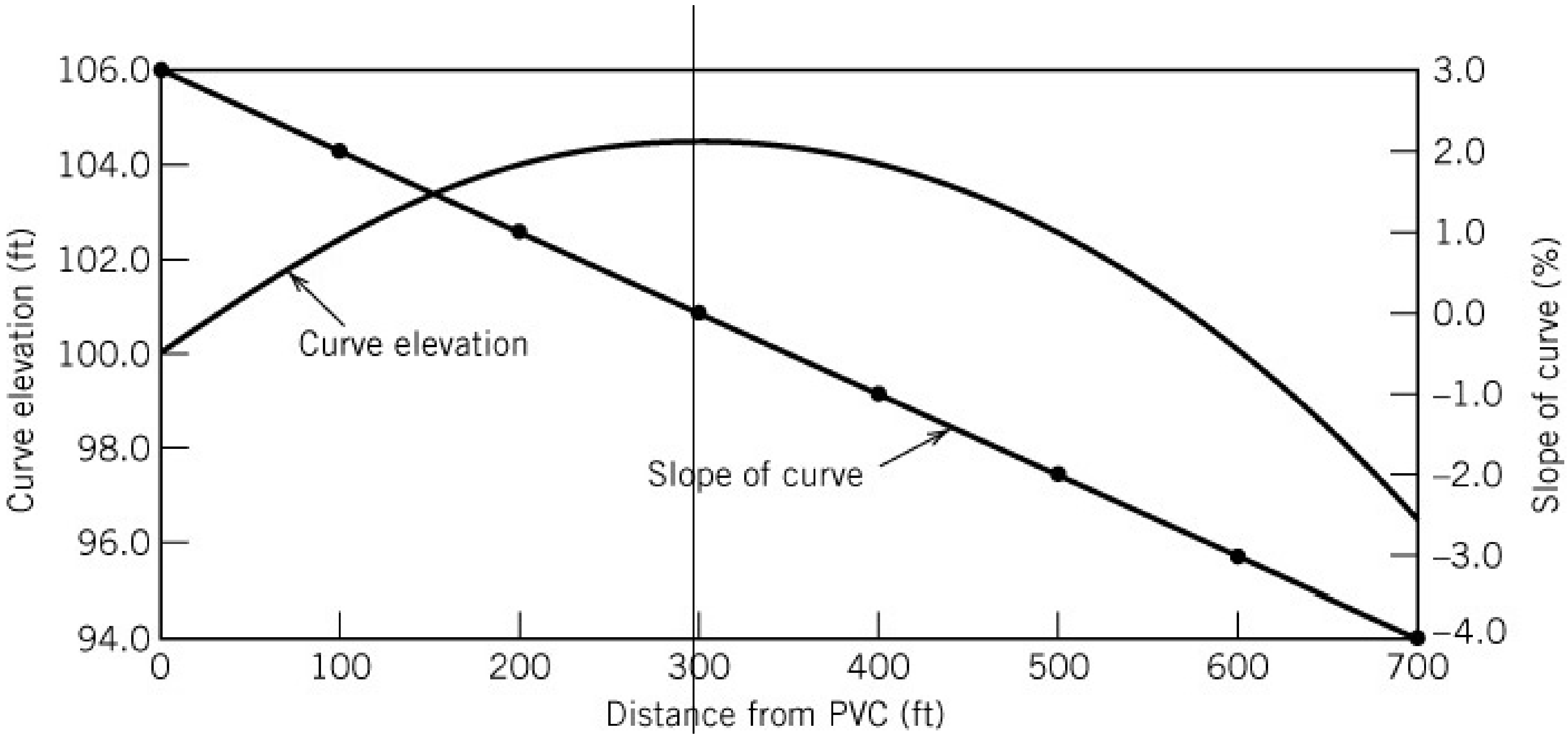
- G_1, G_2 in percent
- L in feet



$$A = |G_1 - G_2|$$

A is the absolute value in grade differences, if grades are -3% and +4%, value is 7

Rate of change of slope different from slope

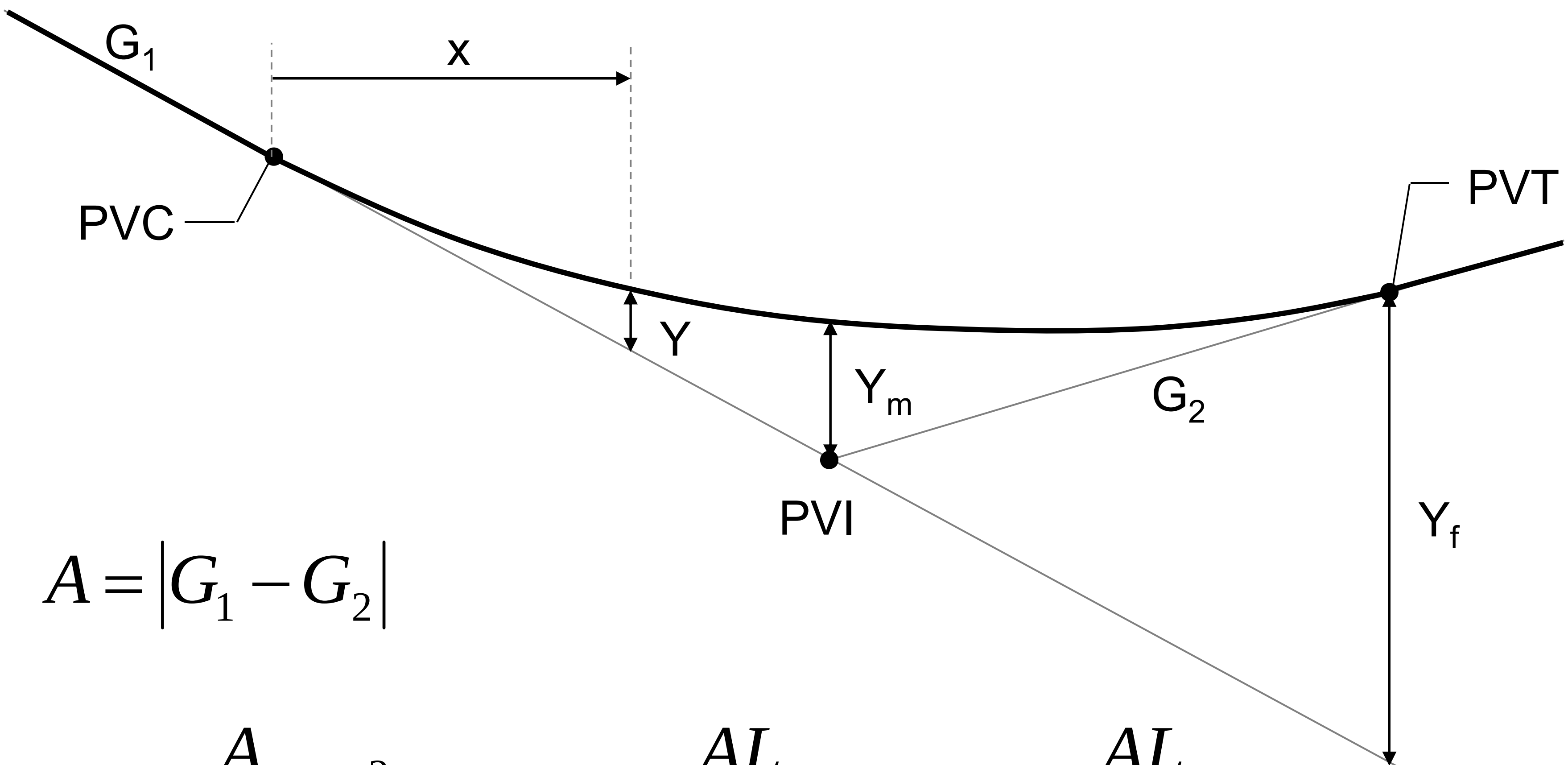


Slope of curve at highpoint is 0

Slope of curve changes, but at a constant rate

Other Properties

- G_1, G_2 in percent
- L in feet
- Y versus y



$$A = |G_1 - G_2|$$

$$Y = \frac{A}{200L}x^2 \qquad Y_m = \frac{AL}{800} \qquad Y_f = \frac{AL}{200}$$

Go back to the parabola

$$y = ax^2 + bx + c$$

Other Properties

- **K-Value (defines vertical curvature)**
  - **The number of horizontal feet needed for a 1% change in slope**

$$K = \frac{L}{A}$$

$$high/low\ \ pt. \Rightarrow x = K\left|G_1\right|$$

- G is in percent, x is in feet
- G is in decimal, x is in stations

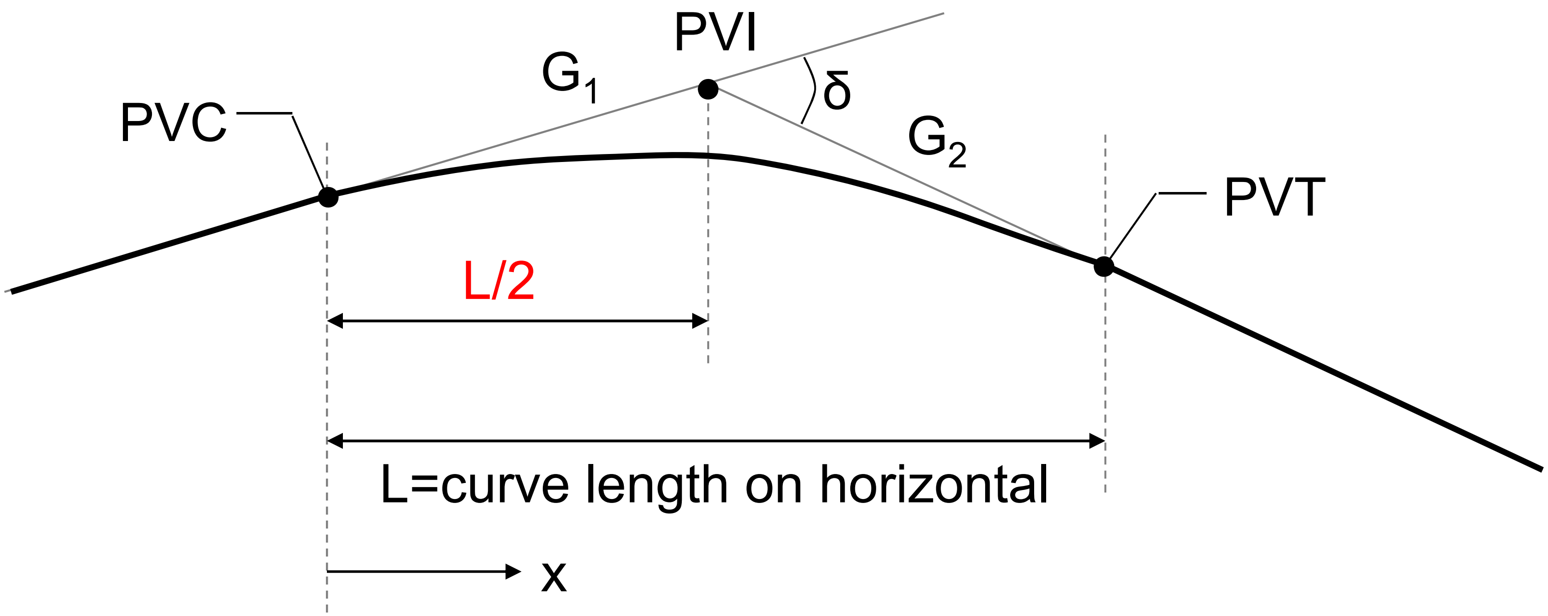
Vertical Curve Fundamentals

- Parabolic function
  - Constant rate of change of slope
  - Implies equal curve tangents

$$y = ax^2 + bx + c$$

- y is the roadway elevation x stations (or feet) from the beginning of the curve

Vertical Curve Fundamentals



PVC and PVT may have some elevation difference

Rate of change of grade is constant, not grade itself

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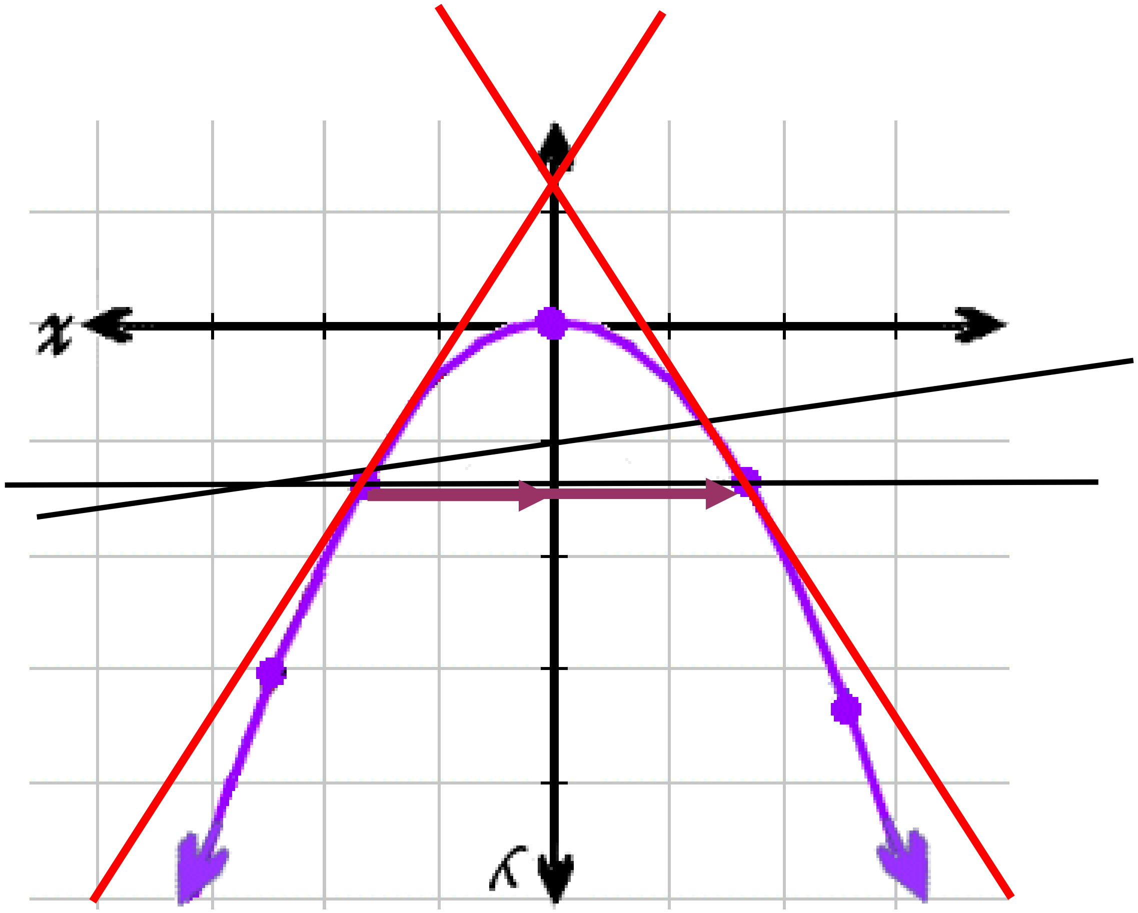
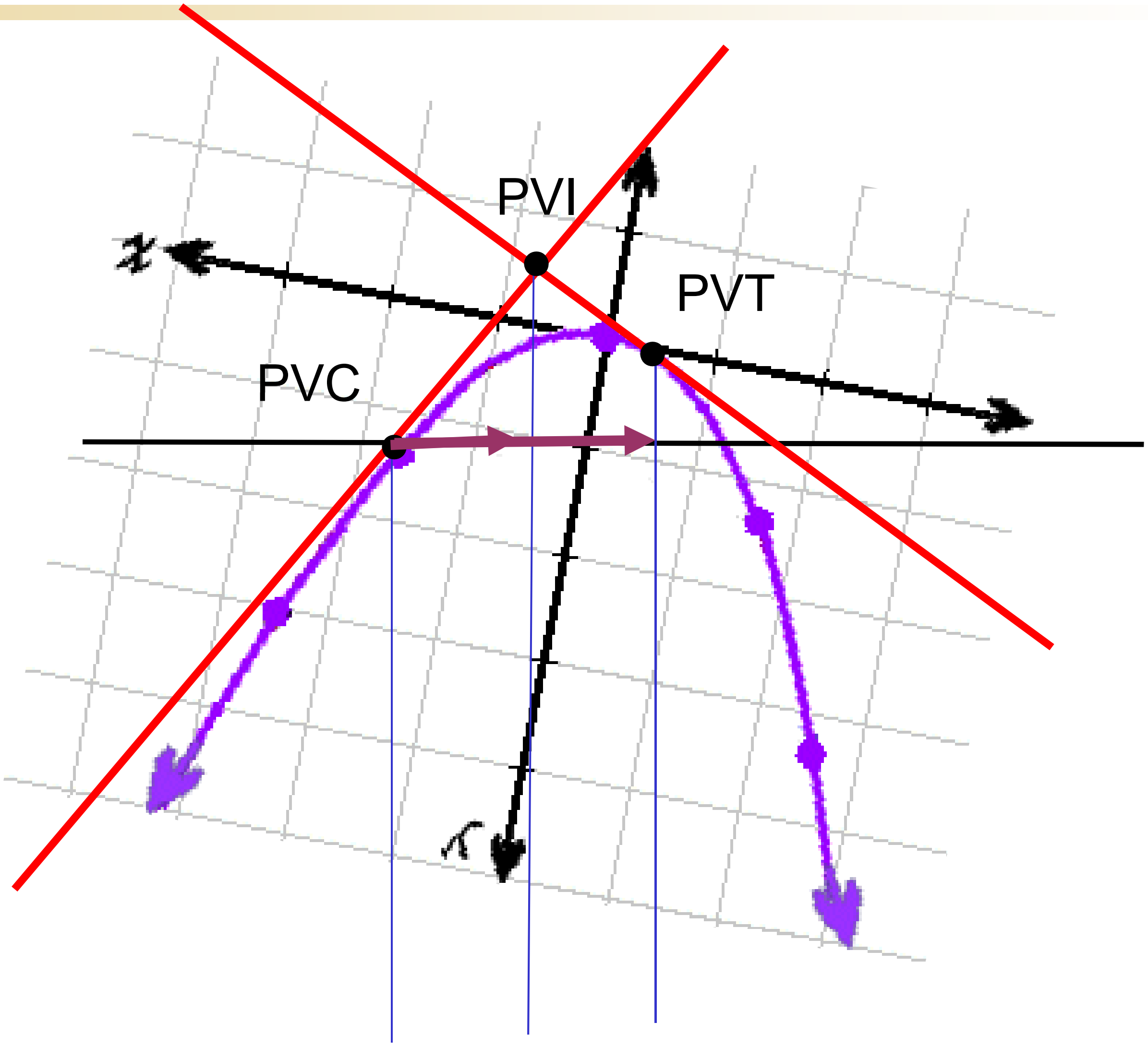
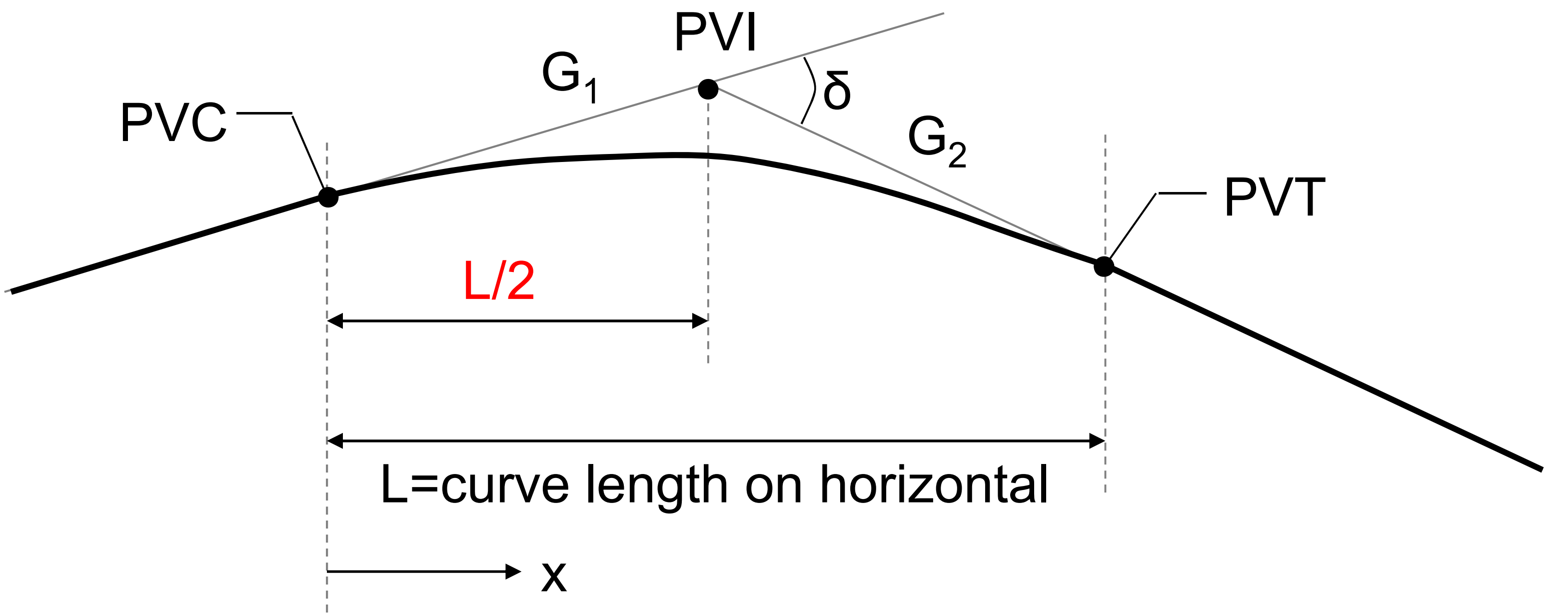



PVI
PVT
PVC

Vertical Curve Fundamentals



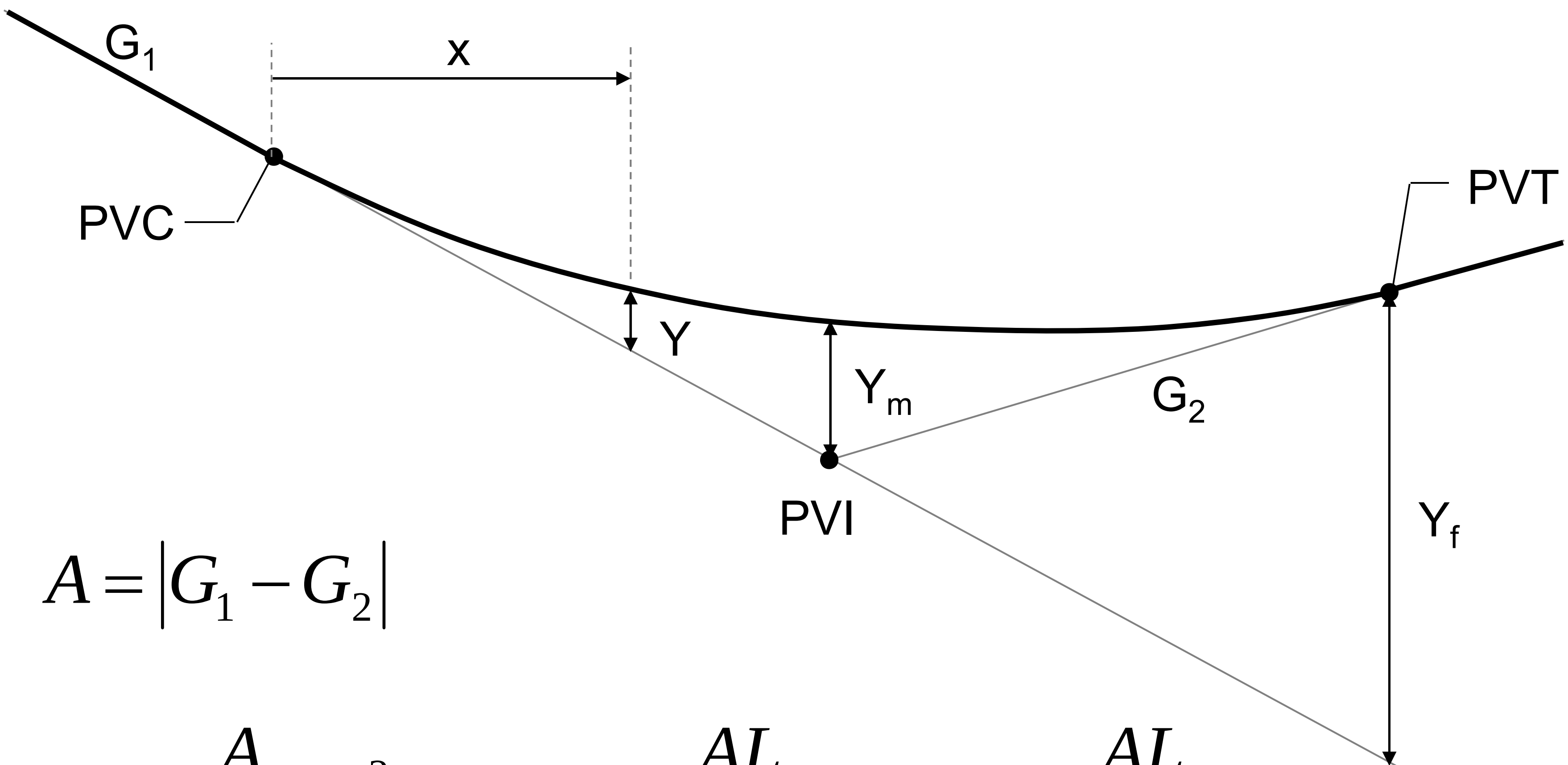
$$y = ax^2 + bx + c$$

Choose Either:

- G_1, G_2 in decimal form, L in feet
- G_1, G_2 in percent, L in stations

Other Properties

- G_1, G_2 in percent
- L in feet



$$A = \left| G_1 - G_2 \right|$$

$$Y = \frac{A}{200L} x^2 \qquad Y_m = \frac{AL}{800} \qquad Y_f = \frac{AL}{200}$$

Other Properties

- **K-Value (defines vertical curvature)**
  - **The number of horizontal feet needed for a 1% change in slope**

$$K = \frac{L}{A}$$

$$high/low\ \ pt. \Rightarrow x = K\left|G_1\right|$$

  - **Small K – tighter curves, less L for same A, slower speeds**
  - **Larger K – gentler curves, more L for same A, higher speeds**

Design Controls for Crest Vertical Curves

Metric				US Customary			
Design speed (km/h)	Stopping sight distance (m)	Rate of vertical curvature, K[a]		Design speed (mph)	Stopping sight distance (ft)	Rate of vertical curvature, K[a]	
		Calculated	Design			Calculated	Design
20	20	0.6	1	15	80	3.0	3
30	35	1.9	2	20	115	6.1	7
40	50	3.8	4	25	155	11.1	12
50	65	6.4	7	30	200	18.5	19
60	85	11.0	11	35	250	29.0	29
70	105	16.8	17	40	305	43.1	44
80	130	25.7	26	45	360	60.1	61
90	160	38.9	39	50	425	83.7	84
100	185	52.0	52	55	495	113.5	114
110	220	73.6	74	60	570	150.6	151
120	250	95.0	95	65	645	192.8	193
130	285	123.4	124	70	730	246.9	247
				75	820	311.6	312
				80	910	383.7	384

[a] Rate of vertical curvature, K, is the length of curve per percent algebraic difference in intersecting grades (A). K = L/A

from AASHTO's *A Policy on Geometric Design of Highways and Streets 2004*

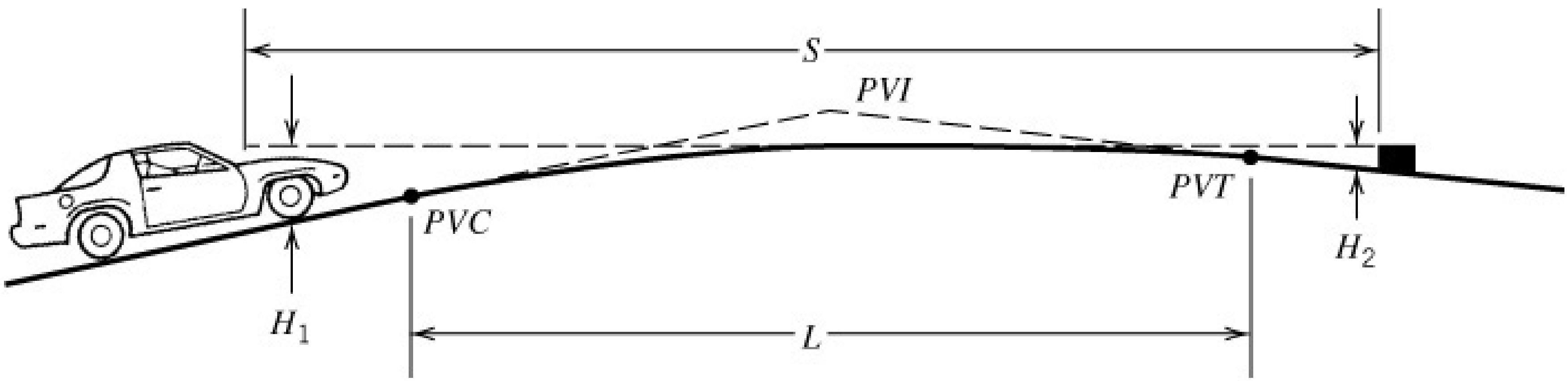
Stopping Sight Distance (SSD)

- Practical stopping distance plus distance travelled during driver perception/reaction time
- Distance travelled along the roadway
- Use this to determine necessary curve length

$$SSD = \frac{V_1^2}{2g\left(\frac{a}{g} \pm G\right)} + V_1 \times t_r$$

Sight Distance (S)

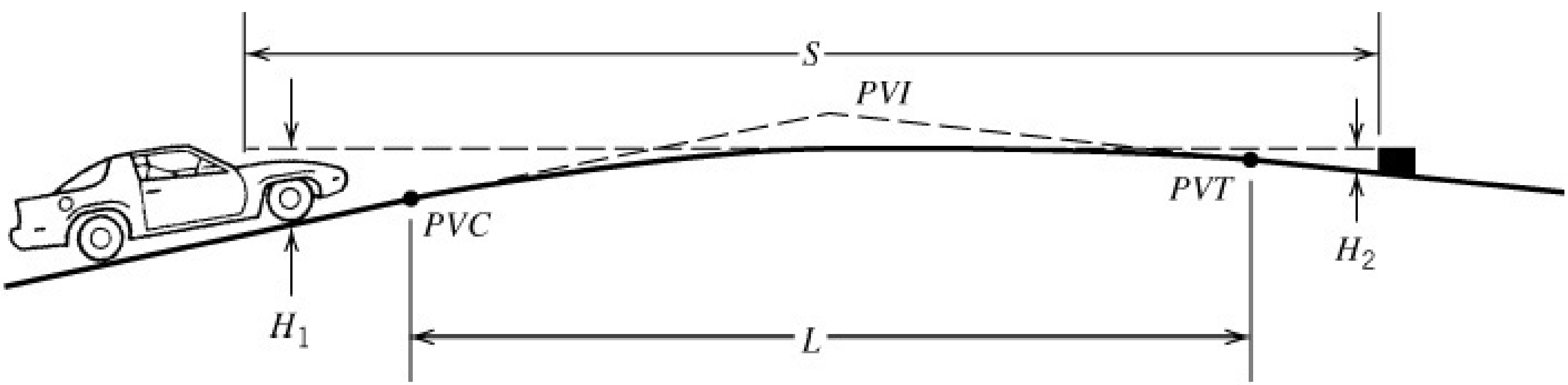
- **Horizontal distance between driver of height H_1 and a visible object of height H_2**



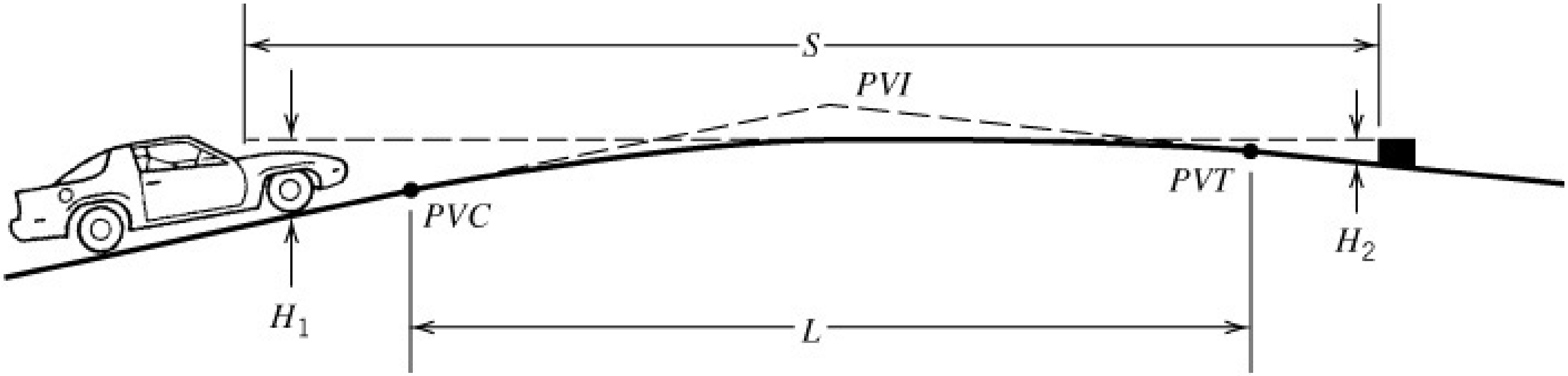
- **Want to design the roadway such that length of curve, L, allows a driver to observe an object with enough time to stop to avoid it (S=SSD).**

Roadway Design

- **Want to design the roadway such that length of curve, L, allows a driver to observe an object with enough time to stop to avoid it.**
- **Set SSD = S.**
- **Approximation works in our favor.**



Crest Vertical Curves



For S < L

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

For S > L

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

Crest Vertical Curves

- **Assumptions for design**
  - **h_1 = driver's eye height = 3.5 ft.**
  - **h_2 = tail light height = 2.0 ft.**

- **Simplified Equations**

For S < L

$$L = \frac{A(S)^2}{2158}$$

For S > L

$$L = 2(S) - \frac{2158}{A}$$

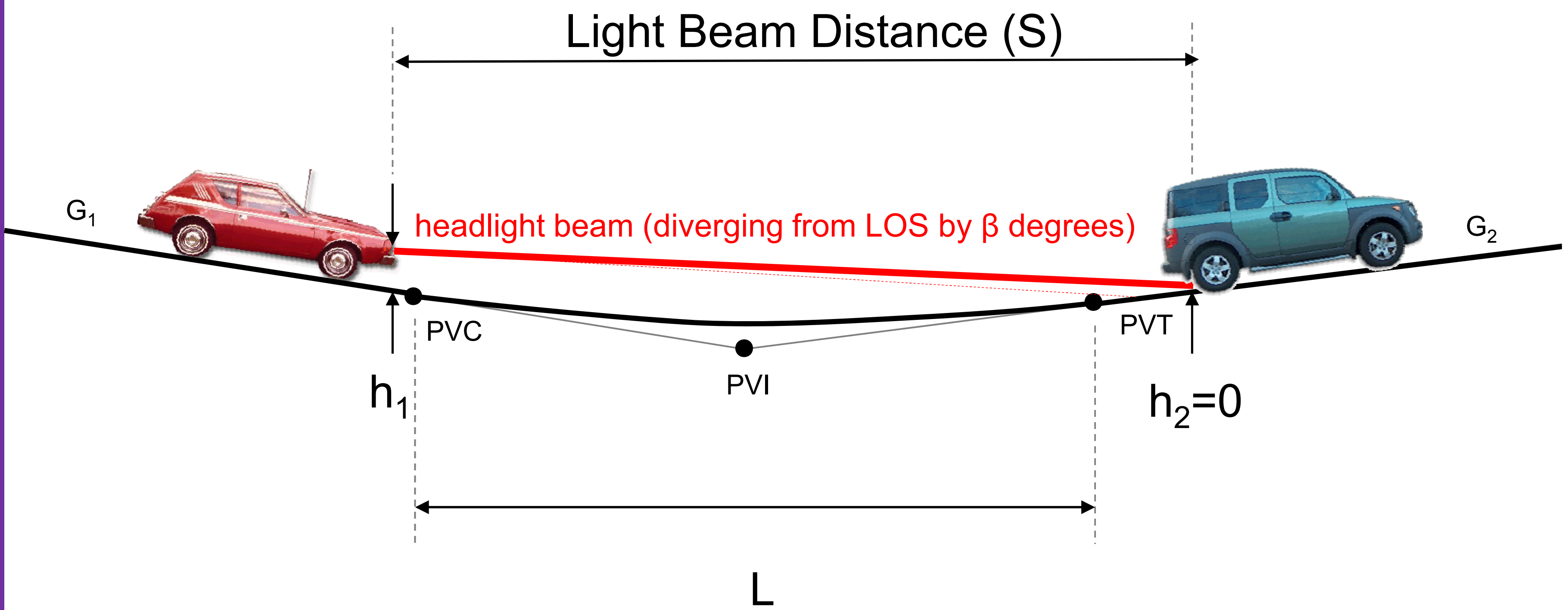
Crest Vertical Curves

- Assume L > S and check
  - Generally true
  - Always safer

$$K = \frac{S^2}{2158}$$

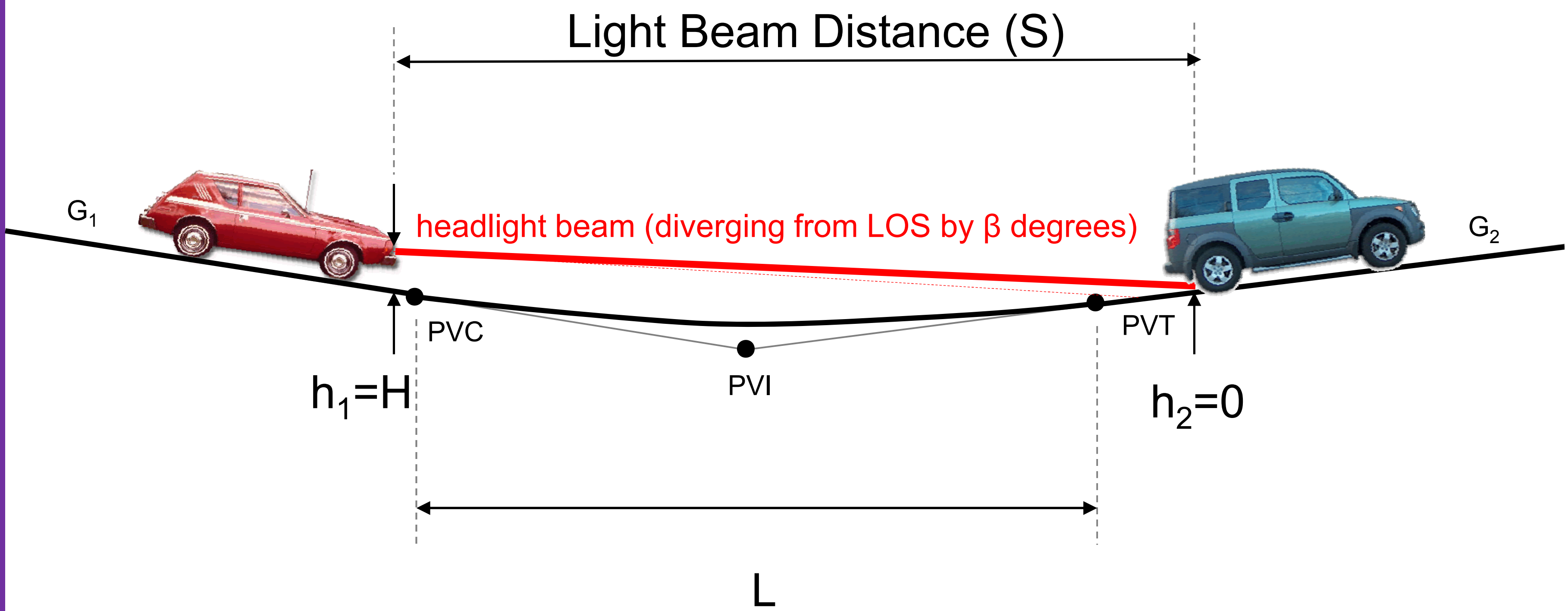
- If assumption does not hold
  - K values cannot be used
  - At low values of A it is possible to get a negative curve length

Sag Vertical Curves



- **Sight distance limited by headlights at night**

Sag Vertical Curves



For S < L

$$L = \frac{A(S)^2}{200(H + S\tan\beta)}$$

For S > L

$$L = 2(S) - \frac{200(H + (SSD)\tan\beta)}{A}$$

Sag Vertical Curves

- **Assumptions for design**
  - **H = headlight height = 2.0 ft.**
  - **β = 1 degree**

- **Simplified Equations**

For S < L

$$L = \frac{A(S)^2}{400 + 3.5(S)}$$

For S > L

$$L = 2(S) - \left(\frac{400 + 3.5(S)}{A}\right)$$

Sag Vertical Curves

- **Assuming L > S…**

$$K = \frac{S^2}{400 + 3.5S}$$

- **Again, set SSD=S**

Design Controls for Sag Vertical Curves

Metric				US Customary			
Design speed (km/h)	Stopping sight distance (m)	Rate of vertical curvature, K[a] Calculated	Design	Design speed (mph)	Stopping sight distance (ft)	Rate of vertical curvature, K[a] Calculated	Design
20	20	2.1	3	15	80	9.4	10
30	35	5.1	6	20	115	16.5	17
40	50	8.5	9	25	155	25.5	26
50	65	12.2	13	30	200	36.4	37
60	85	17.3	18	35	250	49.0	49
70	105	22.6	23	40	305	63.4	64
80	130	29.4	30	45	360	78.1	79
90	160	37.6	38	50	425	95.7	96
100	185	44.6	45	55	495	114.9	115
110	220	54.4	55	60	570	135.7	136
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130	285	72.7	73	70	730	180.3	181
				75	820	205.6	206
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[a] Rate of vertical curvature, K, is the length of curve (m) per percent algebraic difference intersecting grades (A). K = L/A

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Example 1

A car is traveling at 30 mph in the country at night on a wet road through a 150 ft. long sag vertical curve. The entering grade is -2.4 percent and the exiting grade is 4.0 percent. A tree has fallen across the road at approximately the PVT. Assuming the driver cannot see the tree until it is lit by her headlights, is it reasonable to expect the driver to be able to stop before hitting the tree?

1. Assume S<L

$$L = \frac{A(S)^2}{400 + 3.5(S)}$$

2. Solve for S. Roots 146.17 ft and -64.14 ft.

Driver will see tree when it is 146 feet in front of her.

Sag Vertical Curve

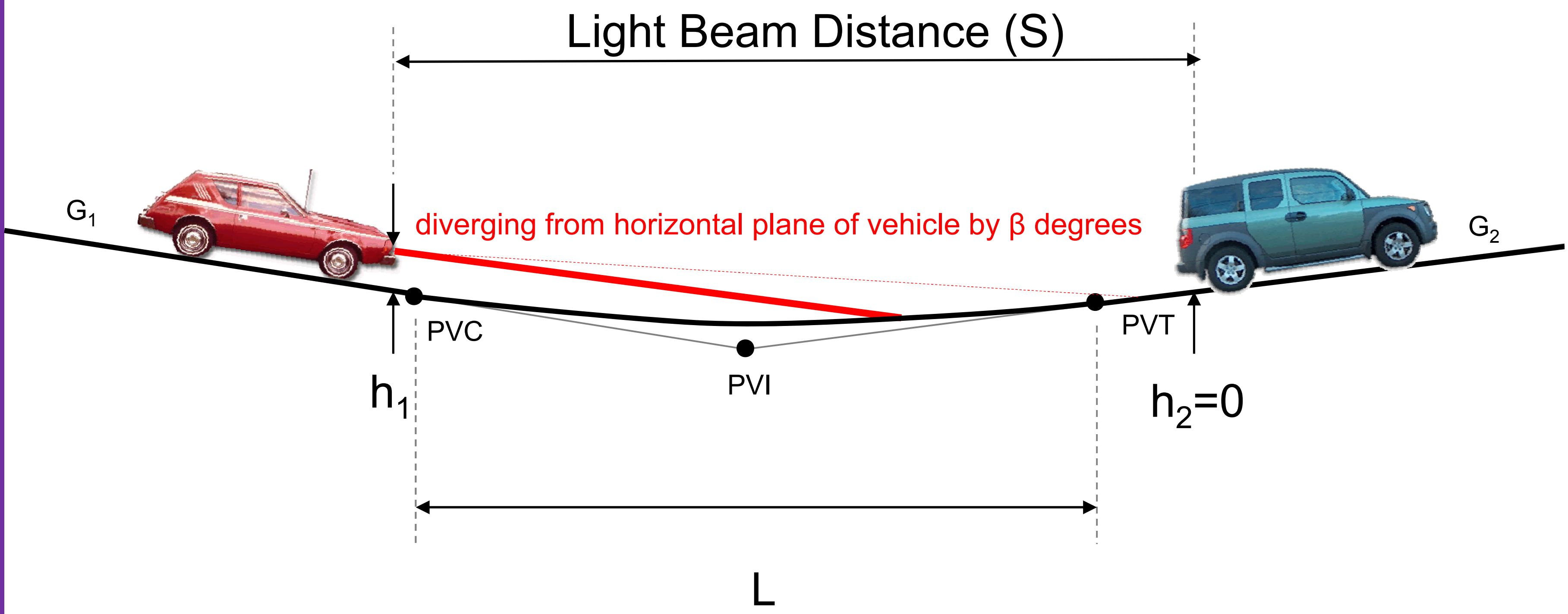
- Required SSD

$$SSD = \frac{V_1^2}{2g\left(\frac{a}{g} \pm G\right)} + V_1 t_r$$

- What do we use for grade?

- 196.53 ft
- assumes 0 grade

Sag Vertical Curves



Daytime sight distance unrestricted

Example 2

A car is traveling at 30 mph in the country at night on a wet road through a 150 ft. long crest vertical curve. The entering grade is 3.0 percent and the exiting grade is -3.4 percent. A tree has fallen across the road at approximately the PVT. Is it reasonable to expect the driver to be able to stop before hitting the tree?

1. Assume S<L
2. A=6.4

$$L = \frac{A(S)^2}{2158}$$

3. S=+/- 224.9 ft. But our curve only 150 ft. So assumption wrong.

Crest Vertical Curve

$$L = 2(S) - \frac{2158}{A}$$

$$SSD = \frac{V_1^2}{2g\left(\frac{a}{g} \pm G\right)} + V_1 t_r$$

- **S = 243 ft**
- **SSD = 196.53 ft**

- **Yes she will be able to stop in time.**

Example 3

A roadway is being designed using a 45 mph design speed. One section of the roadway must go up and over a small hill with an entering grade of 3.2 percent and an exiting grade of -2.0 percent. How long must the vertical curve be?

Using Table 3.2, for 45 mph, K=61

L = KA = (61)(5.2) = 317.2 ft.

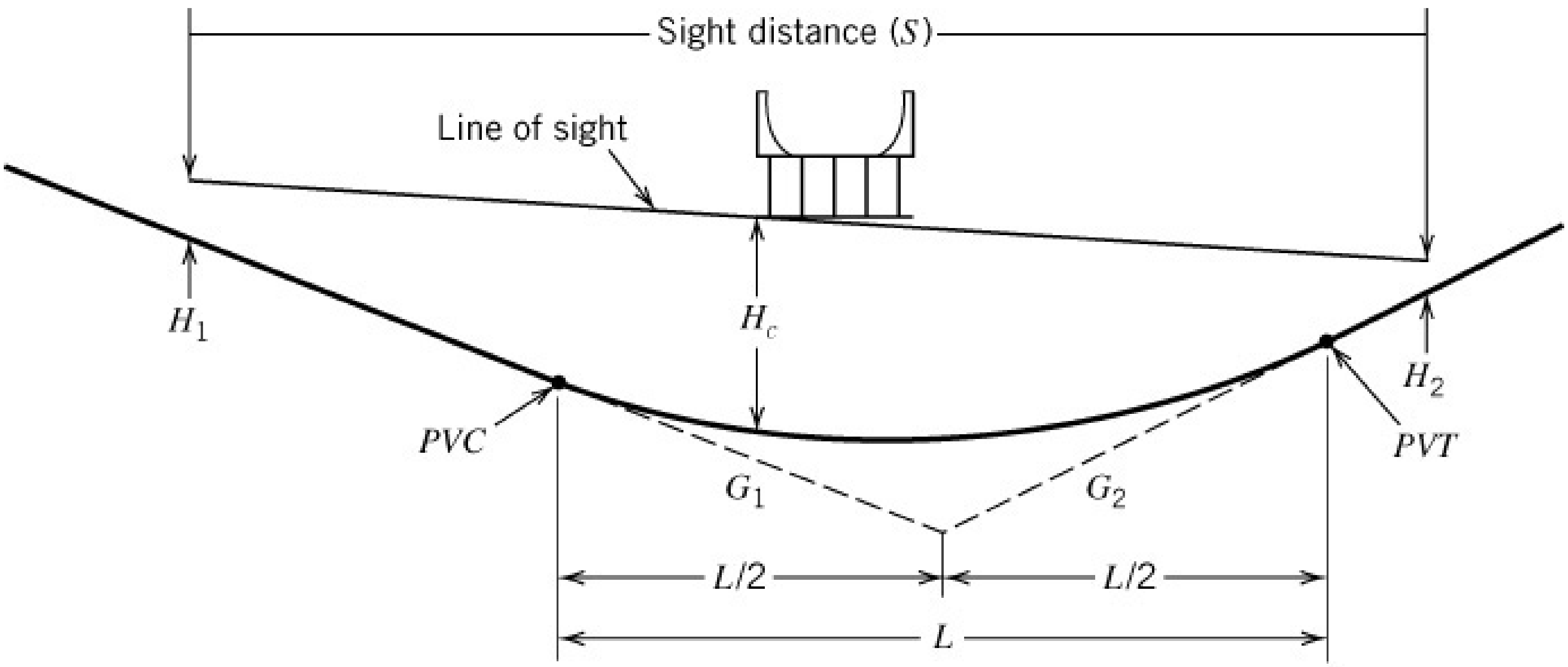
Passing Sight Distance

- **Only a concern on crest curves**
- **On sag curves**
  - **Day: unobstructed view**
  - **Night: headlights can be seen**

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

  - **$H_1 = H_2 = 3.5$ ft, let S=PSD**

Underpass Sight Distance



Underpass Sight Distance

- **On sag curves: obstacle obstructs view**
- **Curve must be long enough to provide adequate sight distance (S=SSD)**

S<L

$$L_m = \frac{A(S)^2}{800\left(H_c - \frac{H_1 + H_2}{2}\right)}$$

S>L

$$L_m = 2S - \frac{800\left(H_c - \frac{H_1 + H_2}{2}\right)}{A}$$