Transportation Engineering

Course Code –CE-422

Contact Hours -3+3

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Terrain

- The topography of the land traversed has an influence on the alignment of roads and streets. Topography affects horizontal alignment, but has an even more pronounced effect on vertical alignment.
- To characterize variations in topography, engineers generally separate terrain into three
  - Level Terrain– flat terrain
  - Rolling Terrain-- truck speed reduces below passenger car
  - Mountainous Terrain– trucks operate at crawl speed

Terrain

- In level terrain, highway sight distances, as governed by both horizontal and vertical restrictions, are generally long or can be made to be so without construction difficulty or major expense.
- In rolling terrain, natural slopes consistently rise above and fall below the road grade, and occasional steep slopes offer some restriction to normal horizontal and vertical roadway alignment.
- In mountainous terrain, longitudinal and transverse changes in the elevation of the ground with respect to the road level are abrupt, and benching and side hill excavation are frequently needed to obtain acceptable horizontal and vertical alignment.

Grades

- Road and street alignment is influenced by the topography of the traversed land. The objective is to encourage uniform vehicle operation and for this it is necessary to provide proper grades and vertical curves.
- Passenger cars can readily negotiate grades as high as 4 to 5% without appreciable loss in speed.
- Speeds decrease progressively with an increase in the ascending grade. Passenger car speeds are generally higher on downgrades than on level sections.
- Truck speeds, on the other hand, are influenced greatly by grades.

Grades

- On downgrades, truck speeds increase by about 5% and decrease about 7% or more on upgrades as compared with operation on level sections.
- AASHTO (2004) provide the maximum grade control guide lines for variable design speeds for different types of roads and traffic. Maximum grades of about 5% are considered appropriate for a design speed of 110 km/h (70 mph). For speed of 50 km/h (30 mph), maximum grades are in the range of 7 to 12% depending on topography, with an average of about 8%.

Maximum Grades and Critical Length

- Maximum grade in itself is not a complete design control. The length of a particular grade should also be considered.
- Critical length is the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed. If efficient operation is to be maintained, design adjustments, such as changes in location to reduce grades or provision of additional lanes, should be made.

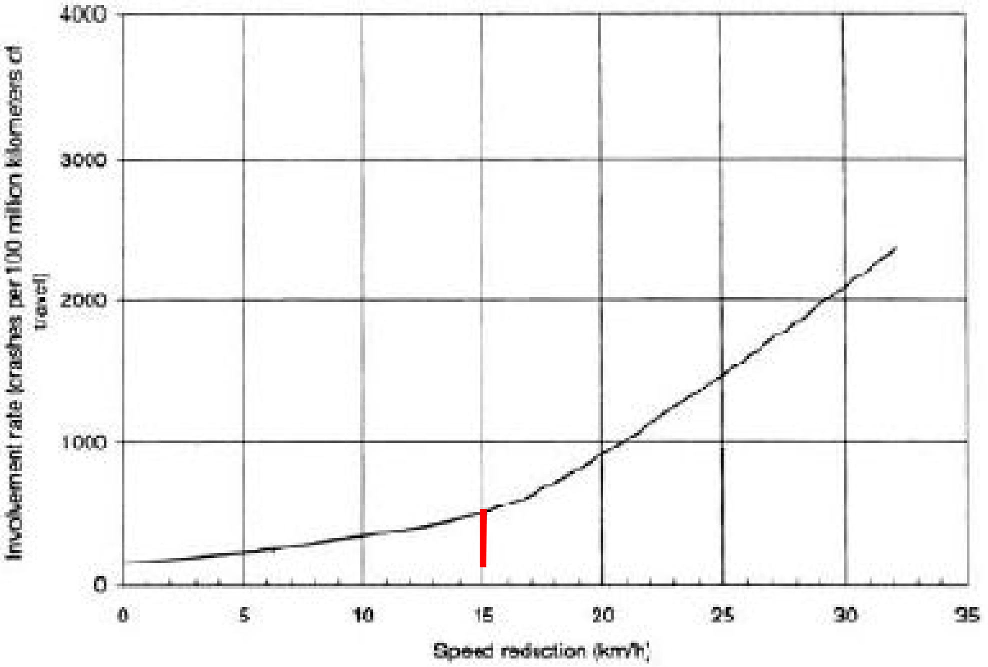
Minimum Grades

- Flat grades can typically be used on uncurbed highways where the cross slopes is adequate to drain the pavement surface laterally. With curbed highways, longitudinal grades should be provided to facilitate surface drainage.
- An appropriate minimum grade is typically 0.5 percent, but grades of 0.30 percent may be used.

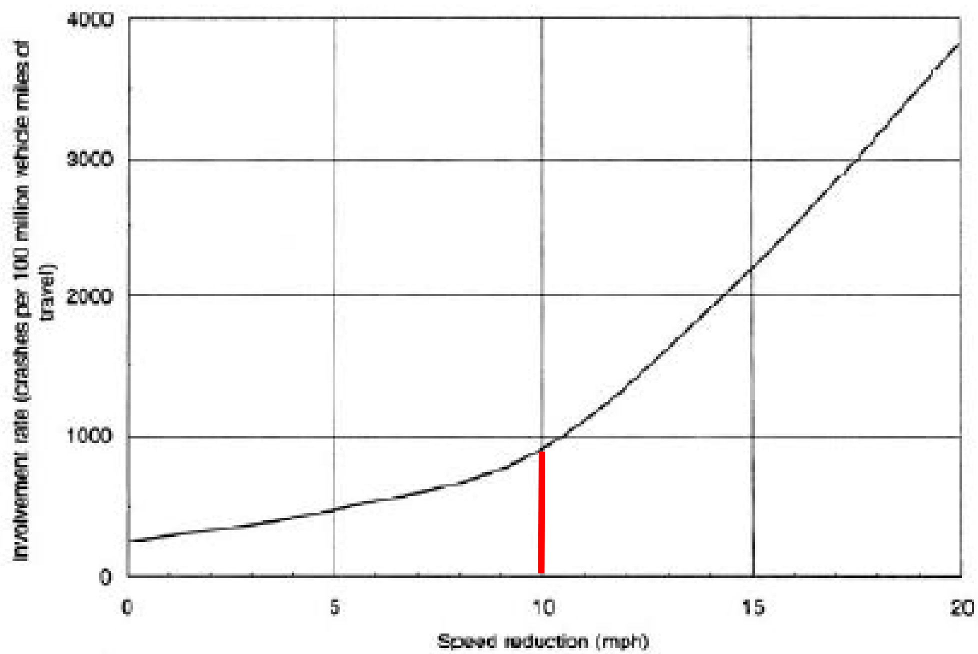
Deviation from Average Speed

- It has been demonstrated that regardless of the average speed on the highway, the greater a vehicle deviates from the average speed, the greater its chances of becoming involved in an accident.
- The ideal case would be when all traffic operates at average running speed, but this is not practical.
- The criterion for determining the critical length of grade is reduction in speed of the truck below average running speed.

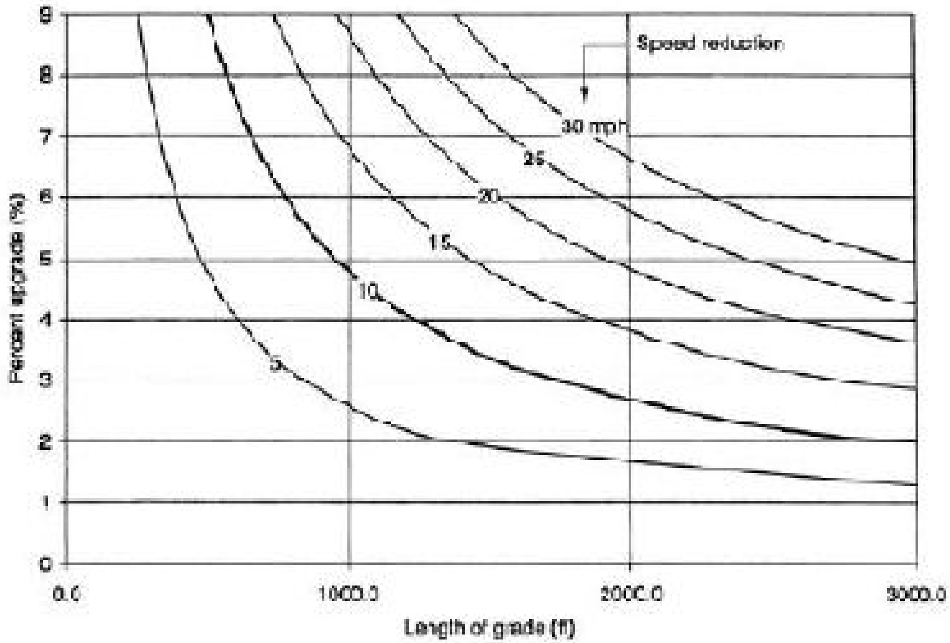
Deviation from Average Speed

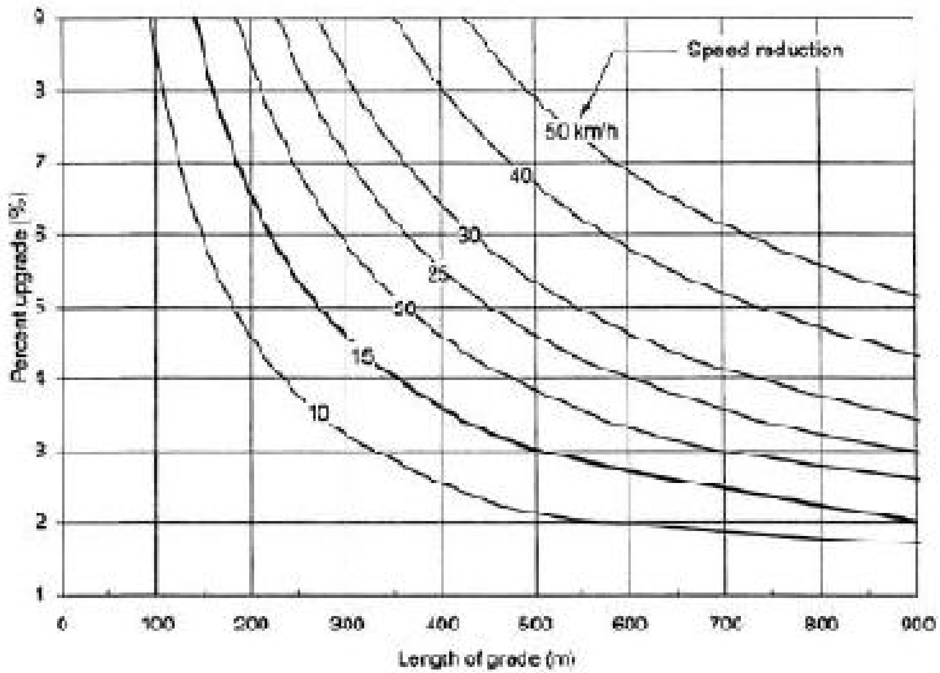


An examination of figure shows that the accident involvement rate increases significantly when the truck speed reduction exceeds 15 km/h (10 mph). Based on this observation, it is recommended that a 15 km/h (10 mph) as speed reduction criterion be used as the general design guide for determining critical lengths of grade.



The length of any given grade that will cause the speed of a representative truck 120 kg/kW (200 lb/hp) entering a grade at 110 km/h (70 mph) to be reduced below the average running speed of all traffic is shown. The curve showing a 15 km/h (10-mph) speed reduction is the general design grade for determining critical grade lengths.





Special facilities for Heavy Vehicles on Steep Grades

- Climbing Lane
  - An extra lane, called a climbing lane on the upgrade side of a two-lane highway, is desirable where the length of the grade causes a reduction of 15 km/h (10 mph) or more in the speed of loaded vehicles. Such provision is justified when the traffic volumes are heavy and the percentage of vehicles with large weight/horsepower ratios is high.
  - The *Highway Capacity Manual* (TRB,2000) and AASHTO (2004) should be consulted for determining the level of service desired on a particular two-lane highway with regard to grade and the need for a climbing lane.

Special facilities for Heavy Vehicles on Steep Grades

- Emergency Escape Ramp
  - The provision of an emergency escape ramp on long, descending grades is appropriate for slowing and stopping out-of-control vehicles away from the main stream of traffic.
  - Loss of braking ability through overheating or mechanical failure results in the driver losing control of the vehicle. Figure on next slide illustrates the action of air, inertial, gradient, and rolling resistance on a vehicle. The values for rolling resistance are given in Table in next slide.

Forces acting on Vehicles in Motion

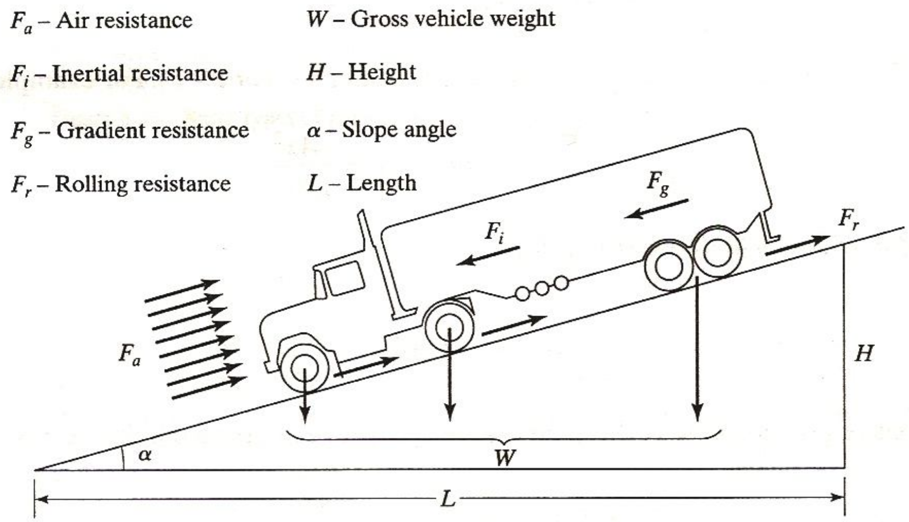


Figure 6-14 Forces Acting on Vehicle in Motion (AASHTO, 2001).

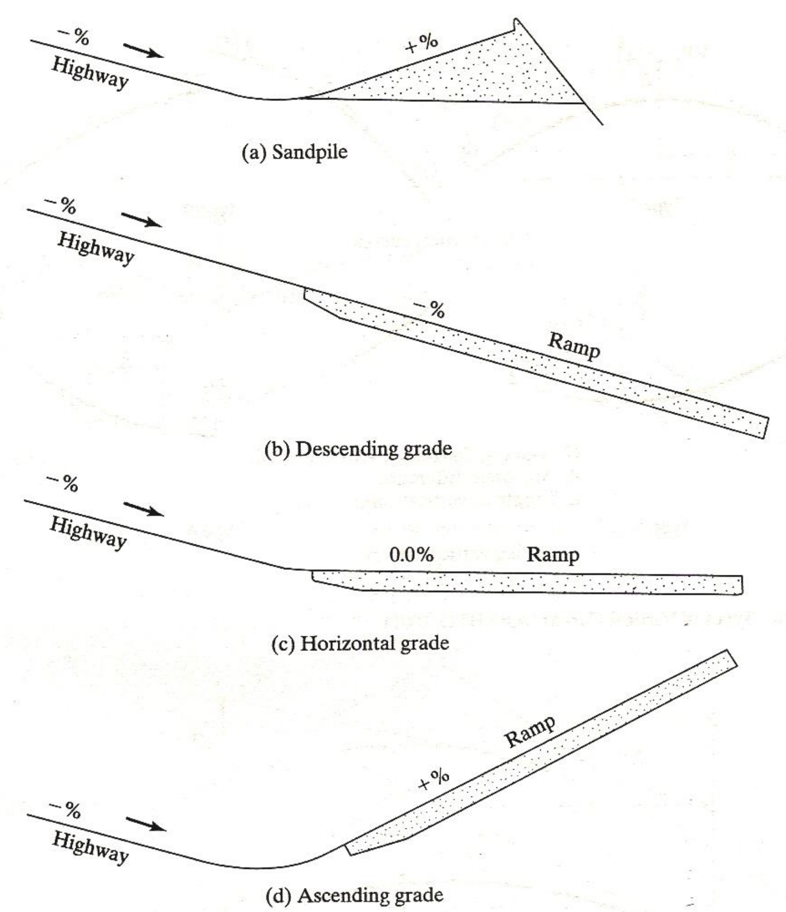
Note GVW is Gross Vehicle Weight

Surfacing material	Metric: Rolling resistance (kg/1000 kg GVM)	Metric: Equivalent grade (%)[a]	US Customary: Rolling resistance (lb/1000 lb GVW)	US Customary: Equivalent grade (%)[a]
Portland cement concrete	10	1.0	10	1.0
Asphalt concrete	12	1.2	12	1.2
Gravel, compacted	15	1.5	15	1.5
Earth, sandy, loose	37	3.7	37	3.7
Crushed aggregate, loose	50	5.0	50	5.0
Gravel, loose	100	10.0	100	10.0
Sand	150	15.0	150	15.0
Pea gravel	250	25.0	250	25.0

[a] Rolling resistance expressed as equivalent gradient.

Emergency Escape Ramps

- Four basic types of emergency escape ramps are commonly used:
  - Sandpile
  - Descending grade
  - Horizontal grade
  - Ascending grade



Note: Profile is along the baseline of the ramp

Vertical Curves

- The gradual change between tangent grades is accomplished by means of anyone of the sag or crest curves.
- Vertical curves should result in a design that is safe, comfortable in operating, pleasing in appearance, and adequate for drainage.
- The provision of ample sight distances for the design speed adopted is the major control factor for safe operation on crest vertical curves. In all cases, the minimum stopping sight distance should be provided.

Crest and Sag Vertical Curves

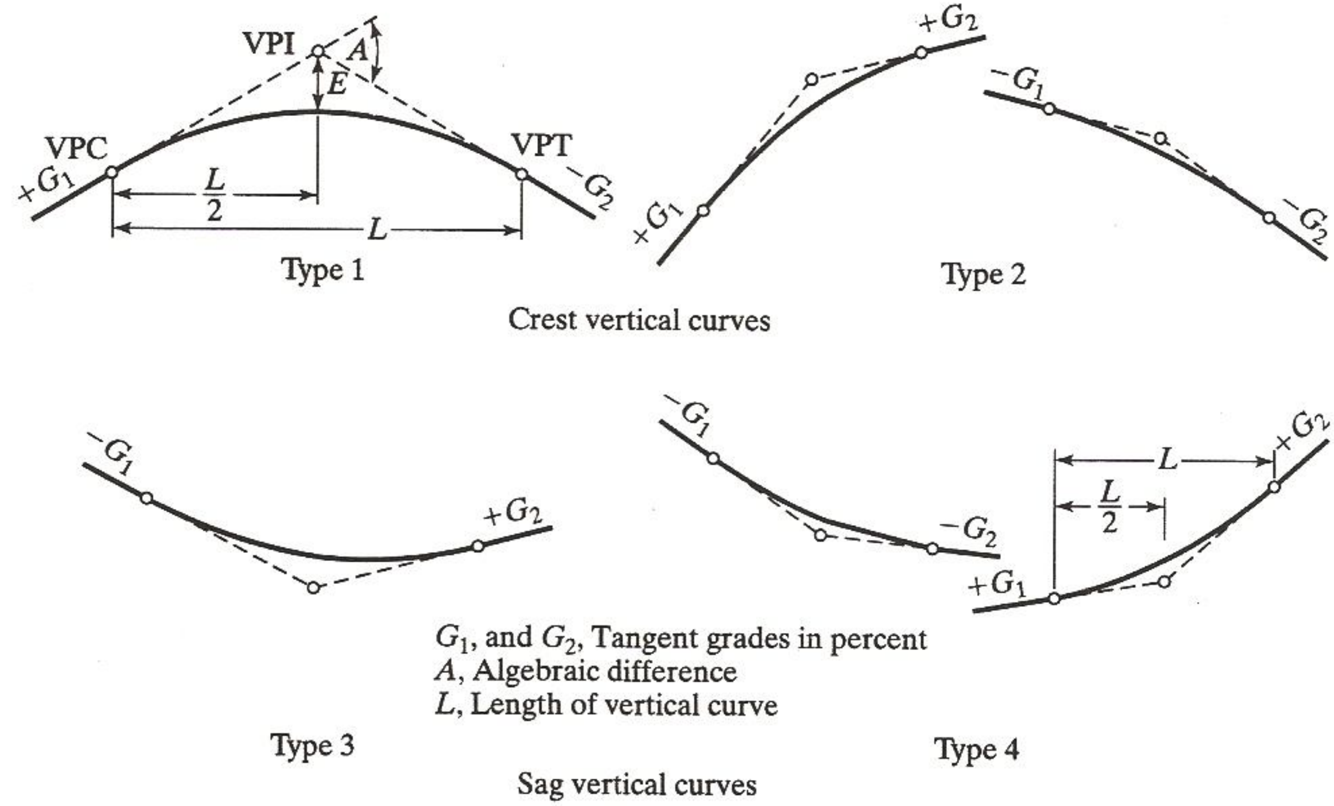
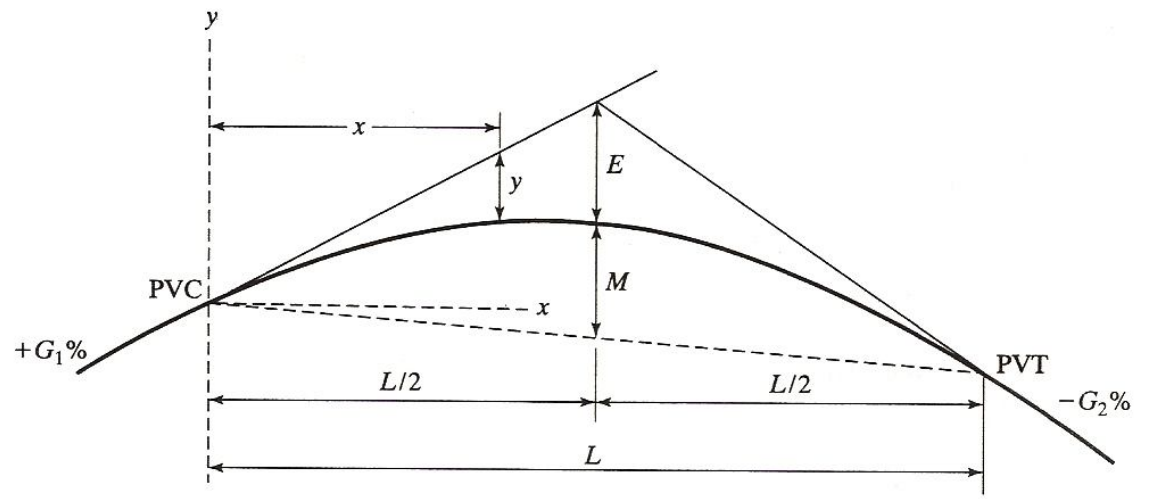


Figure 6-16 Types of Vertical Curves (AASHTO, 2001).

Vertical Curves

- Parabolic curves are usually used in highway design. The vertical offset from the tangent varies as the square of the horizontal distance from the point of vertical curvature or tangency (PVC or PVT). The geometry of a vertical curve is shown



Equal length tangent parabolic curve

Figure 6-17 Geometry of the Vertical Curve (Carter and Homburger, 1978).

Vertical Curves

- The general equation of parabola is

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

- Where "y" is the roadway elevation "x" meters from the beginning of the vertical curve (i.e., from PVC). By definition, "c" is the elevation of the PVC, because x = 0 corresponding to the PVC. In defining "a" and "b" the first derivation of the above equation gives the slope and is

$$\frac{dy}{dx} = 2ax + b \qquad Wher, a = constant = \frac{G_2 - G_1}{400\text{X} \, L/2}$$

Vertical Curves

$$b = \frac{dy}{dx} = G_1$$

- Where G_1 is the initial slope (in m/m). The second derivative of the equation is the rate of change of slope
- The rate of change in grade per station is

$$\frac{d^2 y}{dx^2} = 2a = \frac{A}{L \text{ X } 100}$$

- Where A% is the algebraic difference in grades, $(G_2 - G_1)$, and L, the length of the curve in feet or meters in horizontal projection of the curve on x-axis.

Vertical Curves

$$Midcurve\ \ offset\ \ E = \frac{AL}{800} = M$$

- Other offsets vary as the square of the distances from PVC (or PVT).

$$\frac{y}{x^2} = \frac{E}{\left(L/2\right)^2}\ or\ y = \frac{Ax^2}{200L}$$

- Where "Y" is the offset in meters, "A" is the absolute value of the difference in grades ($|G_1 - G_2|$ expressed in percent), L is the length of the vertical curve in meters, and "x" is the distance from the PVC in meters. In the above equation, 200 is used in the denominator instead of 2 because "A" is expressed in percent instead of m/m.

Vertical Curves

- It is useful to state “y” in terms of E as follows:

$$y = \left(\frac{x}{L} \right)^2 4E$$

- Elevations of points on the vertical curves are easily determined from the expression

$$E_p = E_{pvc} + \left(\frac{G_1}{100} \right) x + \frac{Ax^2}{200L}$$

E_p = Elevation of any point P on the vertical curve, x feet from PVC.

E_{pvc} = Elevation of point of vertical curvature.

Crest Vertical Curves

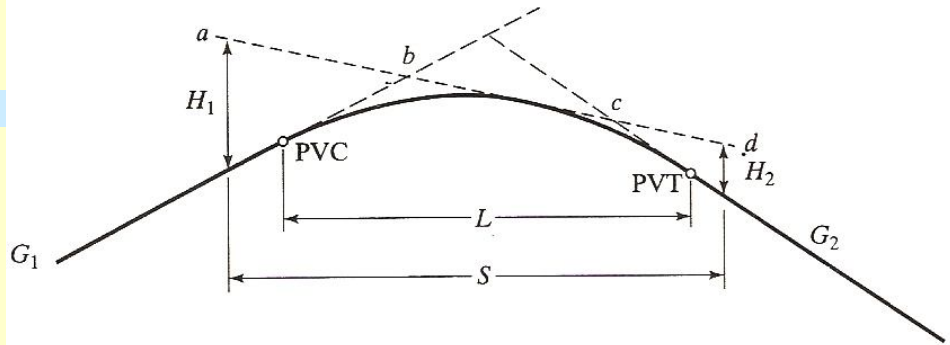
- The minimum lengths of crest vertical curves are dictated by sight distance requirements-that is, the ability of the driver to see an obstacle over the crest of the curve, within safe stopping distance.
- The sight distance criteria generally are satisfactory from the standpoint of safety, comfort and appearance. An exception may be at decision areas, such as sight distance to ramp exit, where long lengths are needed, in such a situation decision sight distance may be required.

Crest Vertical Curves

- The basic equations for the length of a parabolic vertical curve *(L)* are given in terms of the algebraic difference in grades *A* and sight distance S.
- Two cases of a vertical curve, one in which S > *L*, and the other where S < *L*. The height of the driver's eye, H_1 and the height of the object, H_2, are vertical offsets to the tangent line of sight.

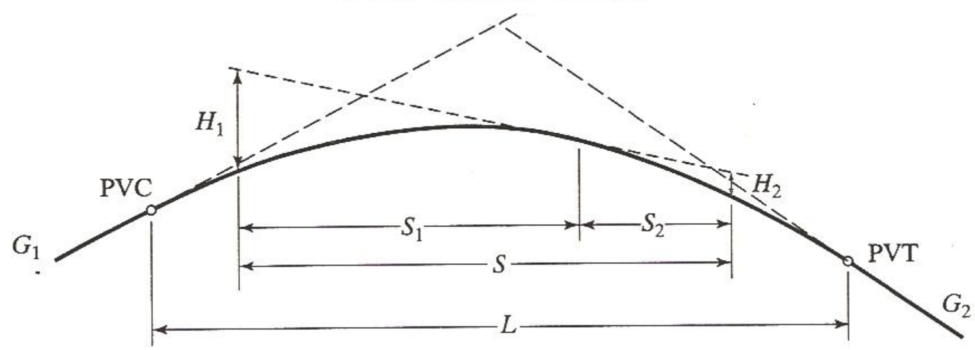
(a) Case 1: Sight distance greater than length of vertical curve ($S > L$)

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



(b) Case 2: Sight distance less than length of vertical curve ($S < L$)

$$L = \frac{AS^2}{100\,(\sqrt{2H_1} + \sqrt{2H_2})^2}$$



Where L = Length of vertical curve, feet or meters
S = Sight distance, feet or meters
A = Algebraic difference in grads, percent
H_1 = Height of eye above roadway surface, feet or meters
H_2 = Height of object above roadway surface, feet or meters

Figure 6-18 Sight Distance of Crest Vertical Curves (Carter and Homburger, 1978).

Crest Vertical Curve

Metric	US Customary	
When S is less than L, $$L=\frac{AS^2}{100\left(\sqrt{2h_1}+\sqrt{2h_2}\right)^2}$$	When S is less than L, $$L=\frac{AS^2}{100\left(\sqrt{2h_1}+\sqrt{2h_2}\right)^2}$$	(3-43)
When S is greater than L, $$L=2S-\frac{200\left(\sqrt{h_1}+\sqrt{h_2}\right)^2}{A}$$	When S is greater than L, $$L=2S-\frac{200\left(\sqrt{h_1}+\sqrt{h_2}\right)^2}{A}$$	(3-44)
where: L = length of vertical curve, m; S = sight distance, m; A = algebraic difference in grades, percent; h_1 = height of eye above roadway surface, m; h_2 = height of object above roadway surface, m	where: L = length of vertical curve, m; S = sight distance, m; A = algebraic difference in grades, percent; h_1 = height of eye above roadway surface, m; h_2 = height of object above roadway surface, m	

Crest Vertical Curve

- When the height of eye and the height of object are 1,080 mm and 600 mm [3.5 ft and 2.0 ft], respectively, as used for stopping sight distance, the equations become:

Metric	US Customary	
When S is less than L, $L=\frac{AS^2}{658}$	When S is less than L, $L=\frac{AS^2}{2158}$	(3-45)
When S is greater than L, $L=2S-\frac{658}{A}$	When S is greater than L, $L=2S-\frac{2158}{A}$	(3-46)

Crest Vertical Curves (Appearance Criteria)

- Although the sight distance requirement is sufficient for the design of crest vertical curves but certain agencies also consider the appearance criteria.
- The problem arises incase of short vertical curves which tend to look like kinks when viewed from a distance.
- Appearance standards vary from agency to agency. Current California stands, require a minimum vertical curve length of 60 m where grade breaks are less than 2 percent or design speeds are less than 60 km/h. Where the grade break is greater than 2 percent and the design speed is greater than 60 km/h, the minimum vertical curve is given by L = 2V, where L is the vertical curve length in meters and V is the design speed in km/h.

Sag Vertical Curves

No single criterion is used for determining lengths of sag vertical curves. The criteria generally used are

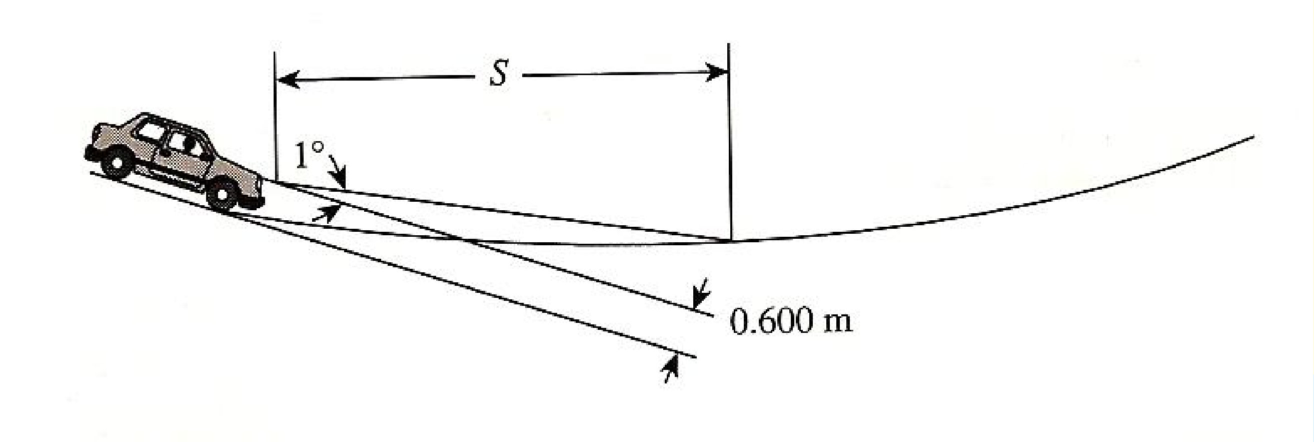
- Headlight sight distance
- Rider comfort
- Drainage control
- A rule of thumb for general appearance.

Sag Vertical Curve (Headlight Sight Distance)

- Headlight sight distance is most commonly used by some agencies for determining the length of sag vertical curves.
- When a vehicle traverses a sag vertical curve at night, the portion of highway lighted ahead is dependent on the position of the headlights and the direction of the light beam.
- A headlight height of 600 mm [2 ft] and a 1-degree upward divergence of the light beam from the longitudinal axis of the vehicle is commonly assumed.

Sag Vertical Curve (Headlight Sight Distance)

- The upward spread of the light beam above the 1-degree divergence angle provides some additional visible length of roadway, but is not generally considered in design. The equations in next slide show the relationships between S, L, and A, using S as the distance between the vehicle and point where the 1-degree upward angle of the light beam intersects the surface of the roadway:



Metric	US Customary	
When S is less than L, $L = \frac{AS^2}{200\left[0.6 + S\left(\tan 1^\circ\right)\right]}$	When S is less than L, $L = \frac{AS^2}{200\left[2.0 + S\left(\tan 1^\circ\right)\right]}$	(3-49)
or, $L = \frac{AS^2}{120 + 3.5\,S}$	or, $L = \frac{AS^2}{400 + 3.5\,S}$	(3-50)
When S is greater than L, $L = 2S - \frac{200\left[0.6 + S\left(\tan 1^\circ\right)\right]}{A}$	When S is greater than L, $L = 2S - \frac{200\left[2.0 + S\left(\tan 1^\circ\right)\right]}{A}$	(3-51)
or, $L = 2S - \left(\frac{120 + 3.5\,S}{A}\right)$	or, $L = 2S - \left(\frac{400 + 3.5\,S}{A}\right)$	(3-52)
where: L = length of sag vertical curve, m; S = light beam distance, m; A = algebraic difference in grades, percent	where: L = length of sag vertical curve, ft; S = light beam distance, ft; A = algebraic difference in grades, percent	

Sag Vertical Curve (Headlight Sight Distance)

- For overall safety on highways, a sag vertical curve should be long enough that the light beam distance is nearly the same as the stopping sight distance. Accordingly, it is appropriate to use stopping sight distances for different design speeds as the value of S in the above equations.

Sag Vertical Curve (Passenger Comfort)

- The effect on passenger comfort of the change in vertical direction is greater on sag vertical curves than on crest vertical curves because gravitational and centripetal forces are in same directions in case of sag ccurves
- Comfort due to change in vertical direction is not readily measured because it is affected appreciably by vehicle body suspension, vehicle body weight, tire flexibility, and other factors.
- Limited attempts at such measurements have led to the broad conclusion that riding is comfortable on sag vertical curves when the centrifugal acceleration does not exceed $0.3 m/s^2$ [$1 ft/s^2$].

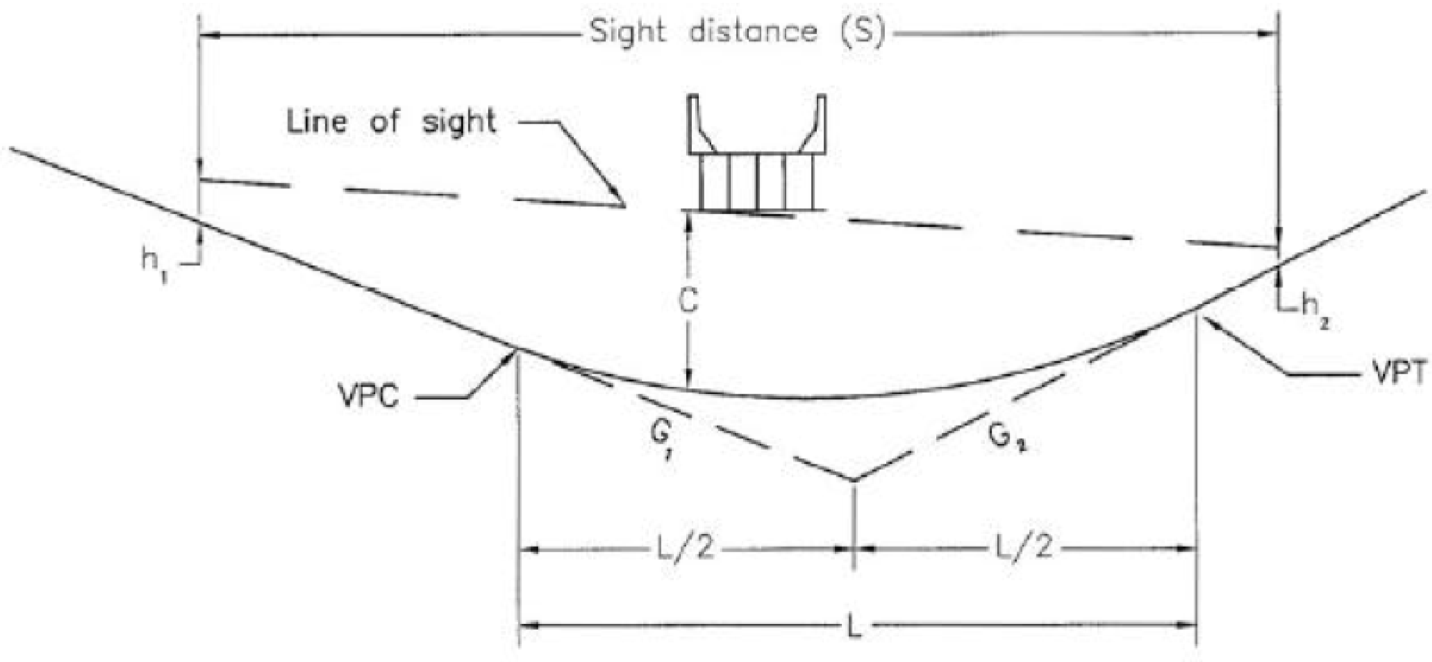
Sag Vertical Curve
(Passenger Comfort)

Metric	US Customary	
$L = \frac{AV^2}{395}$	$L = \frac{AV^2}{46.5}$	(3-53)
where: L = length of sag vertical curve, m; A = algebraic difference in grades, percent; V = design speed, km/h	where: L = length of sag vertical curve, ft; A = algebraic difference in grades, percent; V = design speed, mph	

The length of vertical curve needed to satisfy this comfort factor at the various design speeds is only about 50 percent of that needed to satisfy the headlight sight distance criterion for the normal range of design conditions.

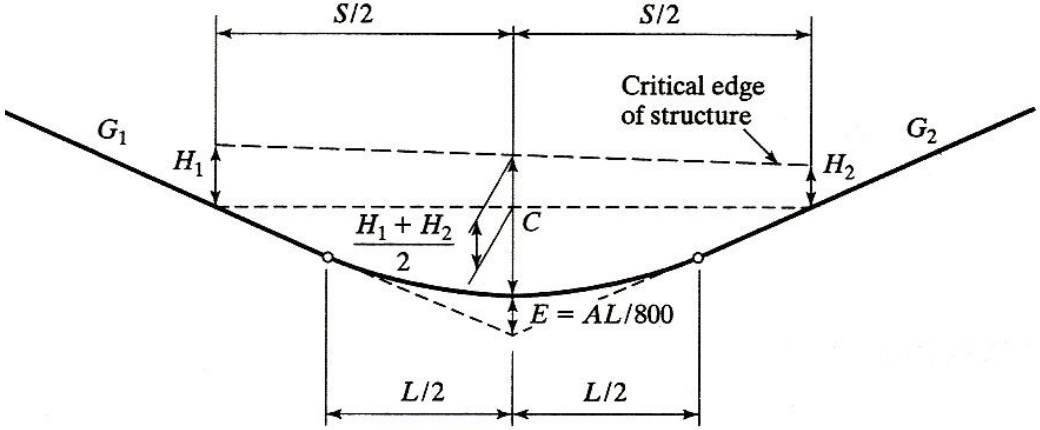
Sight Distance at Undercrossing

- When a sag vertical curve occurs at an underpass, the overhead structure may create a problem by shortening the sight distance. Under such circumstances, the length of vertical curve required for both adequate sight distance and clearance may be determined.



(a) Case 1: Sight distance greater than length of vertical curve ($S > L$)

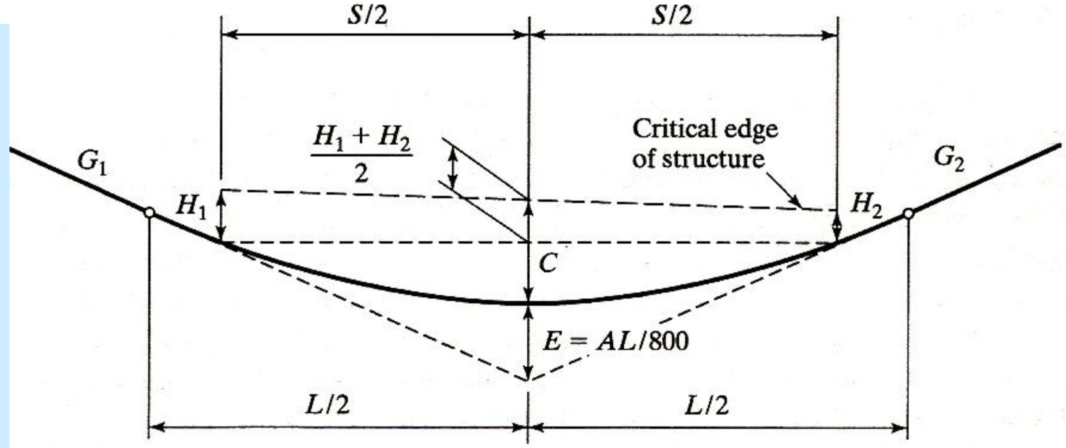
$$L = 2S - \frac{800}{A}\left(C - \frac{H_1 + H_2}{2}\right)^{*}$$



*These equations are valid provided the critical edge of the structure is not more than 200 ft (60 m) from the vertex

(b) Case 2: Sight distance less than length of vertical curve ($S < L$)

$$L = \frac{AS^2}{800}\left(C - \frac{H_1 + H_2}{2}\right)^{-1\,*}$$



where L = Length of vertical curve, feet or meters
A = Algebraic difference in grades, percent
S = Sight distance, feet or meters
C = Vertical clearance of underpass, feet or meters
H_1 = Vertical height or eye above roadway surface, feet or meters
H_2 = Vertical height of object above roadway surface, feet or meters

Using an eye height of 2.4 m (8.0 ft) for a truck driver and an object height of 0.6 m (2.0 ft) for the taillights of a vehicle

Case 1—Sight distance greater than length of vertical curve (S>L):

Metric	US Customary
$$L = 2S - \frac{800\left(C - \left(\frac{h_1 + h_2}{2}\right)\right)}{A}$$	$$L = 2S - \frac{800\left(C - \left(\frac{h_1 + h_2}{2}\right)\right)}{A}$$ (3-54)
where: L = length of vertical curve, m; S = sight distance, m; A = algebraic difference in grades, percent; C = vertical clearance, m; h_1 = height of eye, m; h_2 = height of object, m	where: L = length of vertical curve, ft; S = sight distance, ft; A = algebraic difference in grades, percent; C = vertical clearance, ft; h1 = height of eye, ft; h2 = height of object, ft

Case 2—Sight distance less than length of vertical curve (S<L):

Metric	US Customary	
$L=\dfrac{AS^2}{800\left(C-\left(\dfrac{h_1+h_2}{2}\right)\right)}$	$L=\dfrac{AS^2}{800\left(C-\left(\dfrac{h_1+h_2}{2}\right)\right)}$	(3-55)
where: L = length of vertical curve, m; S = sight distance, m; A = algebraic difference in grades, percent; C = vertical clearance, m; h_1 = height of eye, m; h_2 = height of object, m	where: L = length of vertical curve, ft; S = sight distance, ft; A = algebraic difference in grades, percent; C = vertical clearance, ft; h1 = height of eye, ft; h2 = height of object, ft	

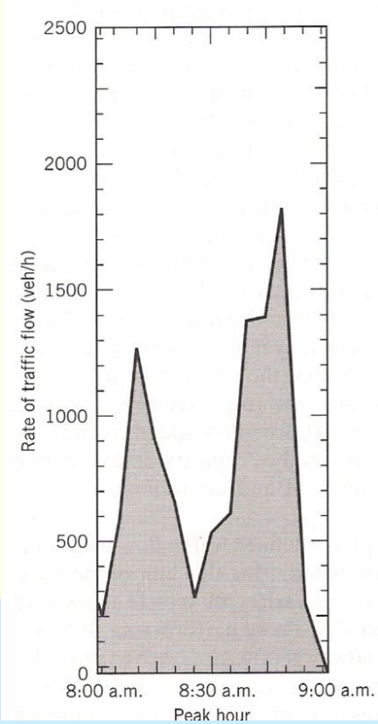
Some Important Definition

- Hourly volume is the actual traffic volume on a roadway in vehicles per hour, given the symbol *V*. Generally, the highest volume in a 24-hour period (i.e., the peak-hour volume) is used for *V* in traffic analysis computations.

Some Important Definition

- *Peak-Hour Factor* The peak-hour factor accounts for the non-uniformity of traffic flow over the peak hour (as shown in Fig.). It is denoted by PHF and is defined as the ratio of the hourly volume *(V)* to the maximum 15- min rate of flow *(V_{15})* expanded to an hourly volume. Therefore

$$PHF = \frac{V}{V_{15} \times 4}$$



Some Important Definition

- Service flow is the actual rate of flow for the peak 15-min period expanded to an hourly volume and expressed in vehicles per hour. Service flow is denoted SF and is defined as

$$SF = \frac{V}{PHF}$$

$$SF = V_{15} \times 4$$

Some Important Definition

- The general unit of measure for traffic is the average daily traffic (ADT), defined as the total volume during a given time period (in whole days), greater than 1 day and less than 1 year, divided by the number of days in that period. The ADT for a highway can be easily determined when continuous traffic counts are maintained.
- The ADT by itself is, however, not a practical measure of traffic because it does not adequately indicate the variation in the traffic in the year, the week, or different hours of the day.

Some Important Definition

- The peak-hour volume is the generally accepted criterion for use in geometric design. It is the traffic volume expected to use the facility and is called the design hourly volume (DHV). It is typically, the 30th highest annual hourly volume. It is denoted by k.

$$K = \frac{DHV}{AADT}$$

Some Important Definition

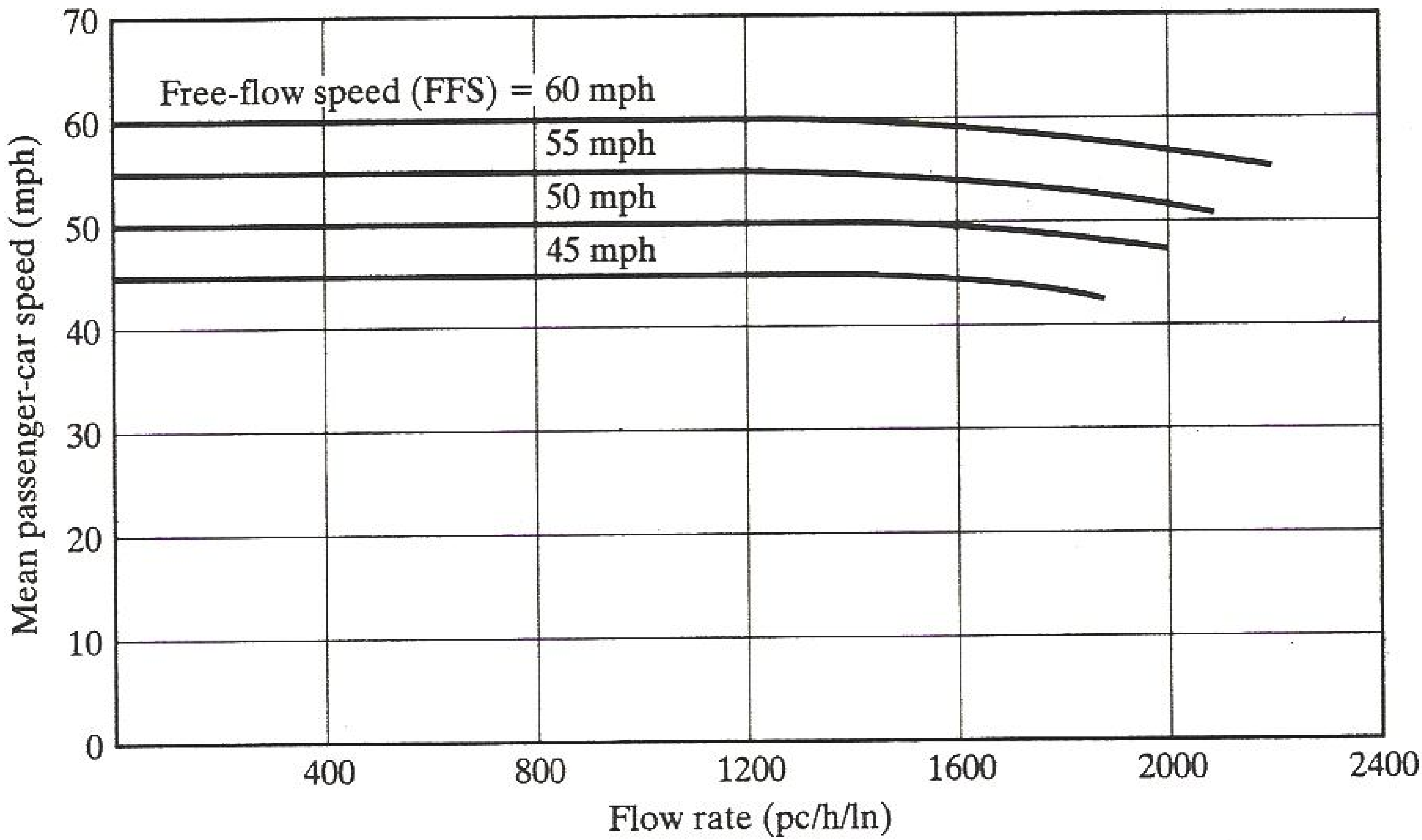
- Design speed is a selected speed used to determine the various geometric design features of the roadway (AASHTO, 2001). Consistent with a desired degree of safety, mobility, and efficiency as well as constrained by environmental quality, economics, aesthetics, and sociopolitical impacts, every effort should be made to use as high a design speed as practicable.

Some Important Definition

- It is necessary to know actual vehicle speeds occurring on a highway section. This is called the running speed and is equal to the distance traveled by a vehicle divided by the time the vehicle is in motion. When vehicle flow is reasonably continuous, the spot speed at a section is the equivalent average running speed. The average spot speed is the arithmetic mean of all traffic speeds at a specified location. On longer sections, several spot speeds measured along the stretch of highway may be averaged to give the average running speed.

Some Important Definition

- Free-flow speed (FFS) is the speed of traffic as density approaches zero. Practically, it is the speed at which drivers feel comfortable traveling under the physical, environmental, and traffic control conditions existing on an uncongested section of freeway or multilane highway.



Speed Flow Relationship on Multilane Highway

Problem

- A+3.9% grade intersect a -1.9% grade at station 20+50.00 and elevation of 1005+00 ft.
- Determine the minimum length of crest vertical curve for a design speed of 50 mph.
- Calculate the location of PVC and the elevation of middle point of the curve.
- Assumption
- Height of eye, H_1 = 3.5 ft and height of object, H_2 = 2.0 ft and SSD = 425 ft.