CHAPTER 4

Geometric Design of Highways

Introduction

- Highway geometric design involves the design of geometric elements of a highway and fixation of standards with respect to various components
- Its dictated within economic limitations to satisfy the requirements of traffic in designing elements such as
    - Cross-section
    - Horizontal alignment
    - Vertical alignment
    - Sight distances
    - Lateral and vertical clearances
    - Intersection,
    - etc.

Introduction

- The safety, efficiency, and economic operation of a highway is governed to a large extent by the care with which the geometric design is worked out
- The engineer has to consider the following points when selecting design standards
  – Volume and composition of traffic in the design year should be the basis of design
  – Faulty geometries are costly to rectify at a later date
  – The design should be consistent and the standards used for the different elements should be compatible with one another
  – The design should embrace all aspects of design including signs, markings, lighting, etc.
  – The road should be considered as an element of the total environment and its location and design should enhance rather than degrade the environment
  – The design should minimize the total transportation cost
  – Safety should be built in the design
  – The design should be enable all road users to use the facility

Design controls and criteria

- The elements of design are influenced by a wide variety of design controls, engineering criteria, and project specific objectives which include
  - Functional classification of the road
  - Design traffic volume and composition
  - Nature of terrain
  - Traffic capacity
  - Design speed
  - Density and character of adjoining land use
  - Economic & Environmental Considerations
  - Road users characteristics
  - Vehicle size and performance
  - Level service to be provided
  - Available fund
  - Safety, etc.

Road Functional Classification

(or Road Hierarchy)

Roads generally serve a multitude of purposes:

- **As through route -** ***for long distance traffic***
- **As local route –** ***for local traffic***
- **In urban and rural areas –urban roads/rural roads**
- **For fast and slow vehicles – 2 wheels to 10+ wheels**
- **As servicing/access roads**
- **For use by pedestrians**
- **For parking areas**
- **For Street Vendors, etc**

Rationale for a hierarchical system

Such a mix of uses Reduces SAFETY, EFFICIENCY, and CAPACITY

Hence a hierarchical road system is necessary

Roads are therefore classified according to their respective functions in terms of the character of the services they are providing

Objectives in setting a hierarchy

- To obtain best use of an existing network
- To ensure that each type of traffic is using the most appropriate route
- To minimize the risk to users and to the natural built environment
- To ensure better management, maintenance regimes and design policies
- To ensure funding for routes is targeted appropriately
- To offer network users a choice for how to travel

Road Hierarchy (most frequently used)

Lower capacity, speed, design standard, …

Characteristics

Primary Distributor — Fast moving long distance through traffic, No frontage development and pedestrians

District Distributor

Local Distributor

Access Roads — Slow moving vehicles, Delivery vehicles, Frontage development, Walking, No through vehicle movement …

Movement is up/down the hierarchy

Road Hierarchy (The Ethiopian way)

Trunk roads	Roads linking centers of international importance and roads terminating at international boundaries and have a present AADT ≥1000 and as low as 100.
Link roads	Roads linking centers of national or international importance and have over 400 - 1000 first year AADT, although values can range between 50-10,000 AADT.
Access roads	Roads linking centers of provincial importance and their first year AADTs between 30-1,000 .
Collector roads	Roads linking locally important centers to each other, to a more important center, or to higher class roads and their first year AADTs between 25-400 .
Feeder roads	Any road link to a minor center such as market and local locations with first year AADT between 0-100.

Nature of Terrain

- The location and geometric design elements such as gradients, sight distance, cross-sections, radius of curvature, speeds, etc. of a highway are affected by topography, physical features, and land use.
- Transverse terrain properties are categorized into four classes as follows:

❑ **FLAT:** Flat or gently rolling country, which offers few obstacles to the construction of a road, having continuously unrestricted horizontal and vertical alignment (transverse terrain slope up to 5 percent).

Nature of Terrain

- **ROLLING:** Rolling, hilly or foothill country where the slopes generally rise and fall moderately and where occasional steep slopes are encountered, resulting in some restrictions in alignment (transverse terrain slope from 5 percent to 25 percent).

Nature of Terrain

- **MOUNTAINOUS:** Rugged, hilly and mountainous country and river gorges. This class of terrain imposes definite restrictions on the standard of alignment obtainable and often involves long steep grades and limited sight distance (transverse terrain slope from 25 percent to 50 percent).

Nature of Terrain

- **ESCARPMENT:** **E**scarpment include situations where switchback roadway sections are used or side hill transverse sections which cause considerable earthwork quantities, with transverse terrain slope in excess of 50 percent.

Traffic Volume and Composition

- Traffic data indicates the service for which the road is being planned and directly affects the geometric elements such as width, alignment, etc,
  - Traffic volume – AADT, ADT, PHV, DHV
  - Directional distribution – the percentage of traffic volume flowing in each direction
  - Traffic composition – the percentage of different types of vehicles in the traffic stream – different types of vehicles are converted into passenger car unit to design a road width
  - Traffic projection – using the design period of a road (5-20 years)a reliable traffic projection should be made considering the following elements

Traffic Volume and Composition

- Traffic projection (cont'd.):–

- Current traffic – currently using the existing road
- Normal traffic growth – anticipated growth due to population growth or change in land use
- Diverted traffic – traffic that switches to a new facility from near by roads
- Converted traffic – traffic resulting from changes of mode
- Change of destination traffic – traffic that has changed to different destination due to new or improved transport and not changes in land use
- Development traffic – traffic due to improvement on adjacent land development that would have taken place had the new or improved road not been constructed
- Induced traffic – traffic that did not previously exist in a any form but results when new or improved transport facilities are provided

Traffic capacity

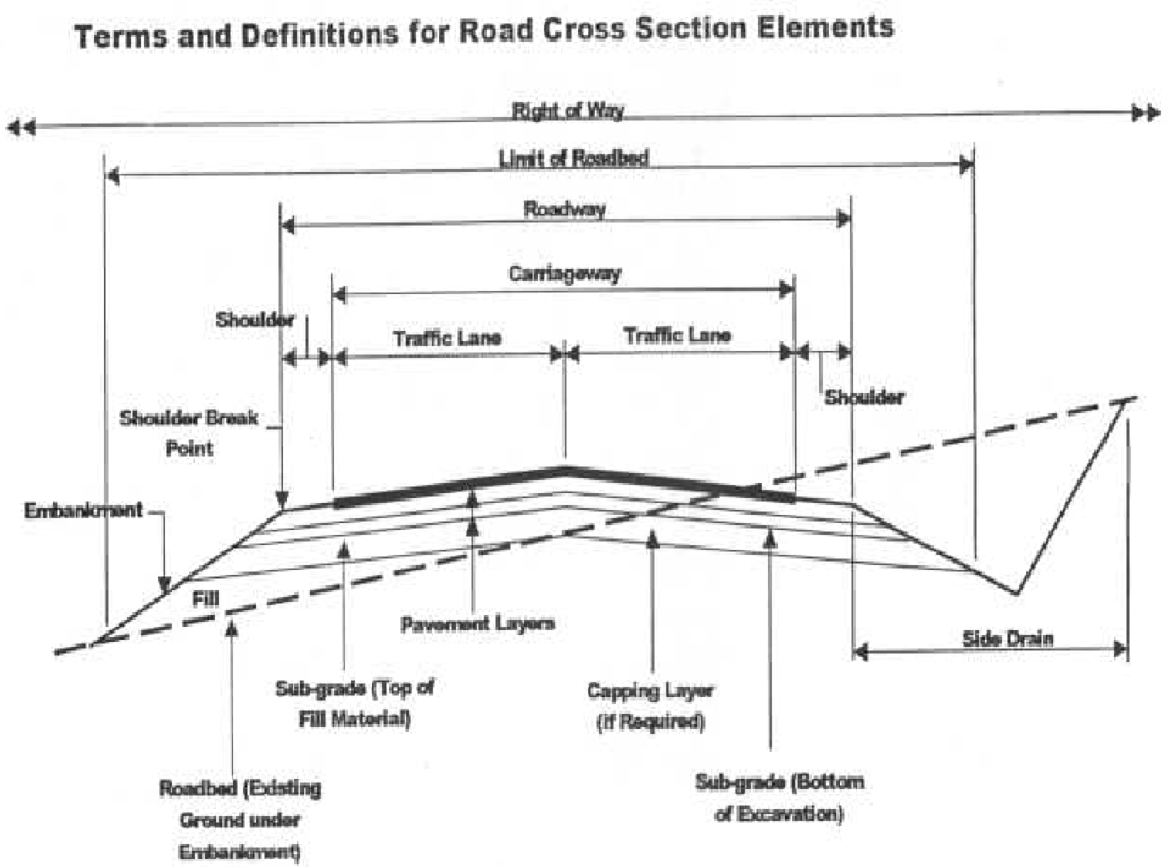
- The maximum traffic flow occurs when the speed falls down to nearly a half of the free-flow speed. Hence it is not desirable to design the road facility for maximum capacity conditions.
- **Factors affecting traffic capacity include:**
    - Roadway factors – geometric characteristics such as number of lanes, lane width, shoulder width, horizontal and vertical alignments, lateral and vertical clearances, design speed, pavement surface conditions etc.
    - Traffic factors – composition of traffic, lane distribution, varaiation in traffic flow, traffic interruptions, etc.
    - Traffic control conditions – traffic signs, traffic signals, traffic regulation, etc.
- Without the consideration of these factors, early attempts were made to determine capacity using

$$C = \frac{1000V}{d}$$

Speed

- The speed that a driver adopts on a road depends on:
  - Physical characteristics of the road and its surroundings
  - Weather conditions in the area
  - Presence of other vehicles and the nature of these vehicles, and
  - Speed limitations placed upon the vehicles either by law or by mechanical devices fitted in vehicles
- Design speed is the max safe speed selected for designing specific section of road considering the terrain, land use, classification of the road, etc.

Elements of Road Cross-section



Elements of Road Cross-section

- Principal elements
  - Traffic lanes
  - Auxiliary lanes – climbing lanes, acceleration and deceleration lanes, etc
  - Shoulders
  - Median (for divided roads)
- Marginal elements include
  - Median and roadside barrier
  - Curbs
  - Gutters
  - Guard rails
  - sidewalks,
  - Side slopes,
  - Cross slopes

Elements of Road Cross-section

- Width of travel lanes
  - Usually vary from 3 to 3.65 m, but occasionally 2.7 m lane width is used in urban areas where the traffic volume is low and there is extreme right-of-way constraints
  - On two way two lane rural roads, accident rate for large trucks increases as the traveled way decreases from 6.5 m
  - The capacity decrease significantly as the lane width decrease from 3.0 m

Elements of Road Cross-section

- Shoulders
    - Serves for an emergency stop of vehicles
    - Used to laterally support the pavement structure
  - Shoulder width
    - Recommended shoulder width is in the range of 1.8 to 2.4 m
    - for highways serving large number of trucks and on highways with high traffic volumes and high speeds, shoulder width of 3.0 to 3.5 m is preferable
    - Minimum shoulder width 0.6 m on the lowest type of roads
  - Shoulders should be flush with the edge of the traveled lane and be sloped to facilitate drainage (2-4 % if paved, 4-6 % if not paved)

Elements of Road Cross-section

- Median – section of divided road that separates lanes in the opposite directions.
- Functions:
    - Provide recovery area during emergency
    - Provide stopping area for left and U-turning vehicles
    - Provide refuge for pedestrians
    - Reduce headlight glare
  - Median can be either raised, flush or depressed
  - Median width vary between 0.6 up to 24 m or more depending on the availability of right-of-way

Elements of Road Cross-section

- Median barrier – a longitudinal structure used to prevent an errant vehicle from crossing the portion of a divided highway separating the traveled way for traffic in the opposite directions
- Roadside barrier – protect vehicles from causing hazards onto roadside and shield pedestrians
- Curbs – raised structures used mainly on urban roads to delineate pavement edge and pedestrian walkways. Curbs are also used:
    - To control drainage
    - Improve aesthetic
    - Reduce right-of-way
  - Are classified as
    - Barrier curbs – relatively high designed for preventing vehicles from leaving the toad
    - Mountable curbs – are designed so that vehicles can cross them

Elements of Road Cross-section

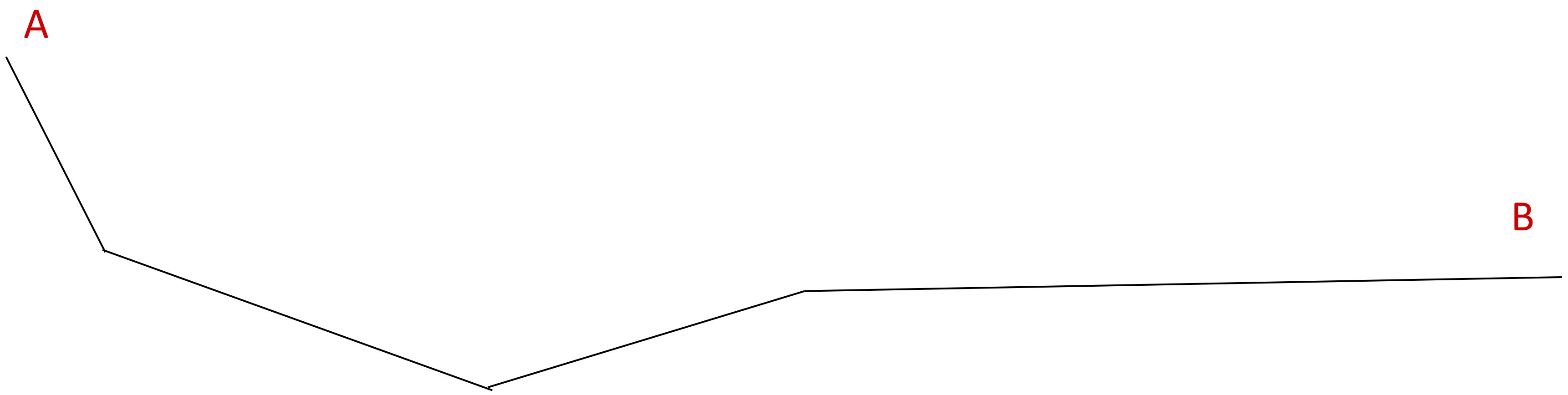
- Gutters – drainage ditches located on the pavement side of a curb to provide the principal drainage facility for the highway
- Guard rails – longitudinal barriers on the outside of sharp curves at sections with high fills (greater than 2.5 m)
- Side walks – provided on urban or rural roads
  - When pedestrian traffic is high along main or high speed roads
  - When shoulders are not provided on arterials even when pedestrian traffic is low
  - In urban areas, sidewalks are provided along both sides of streets to serve pedestrians access to schools, parks, shopping centers, and transit stops.

Elements of Road Cross-section

- Cross-slopes – to enhance the flow of surface water
    - High type pavement – 1.5 –2 %
    - Intermediate type of pavement – 1.5- 3%
- Side slopes – provided for stability of earthworks; the slope varies depending on the material type
- Right-of-way – the total land area required for the construction of the roadway
    - To accommodate all the elements of the road cross-section
    - Planned widening of the road
    - Public utility facilities that will be installed along the highway

Horizontal Alignment

Your Chosen Route



But, the road could not have such an alignment with sharp edges!

Introduction

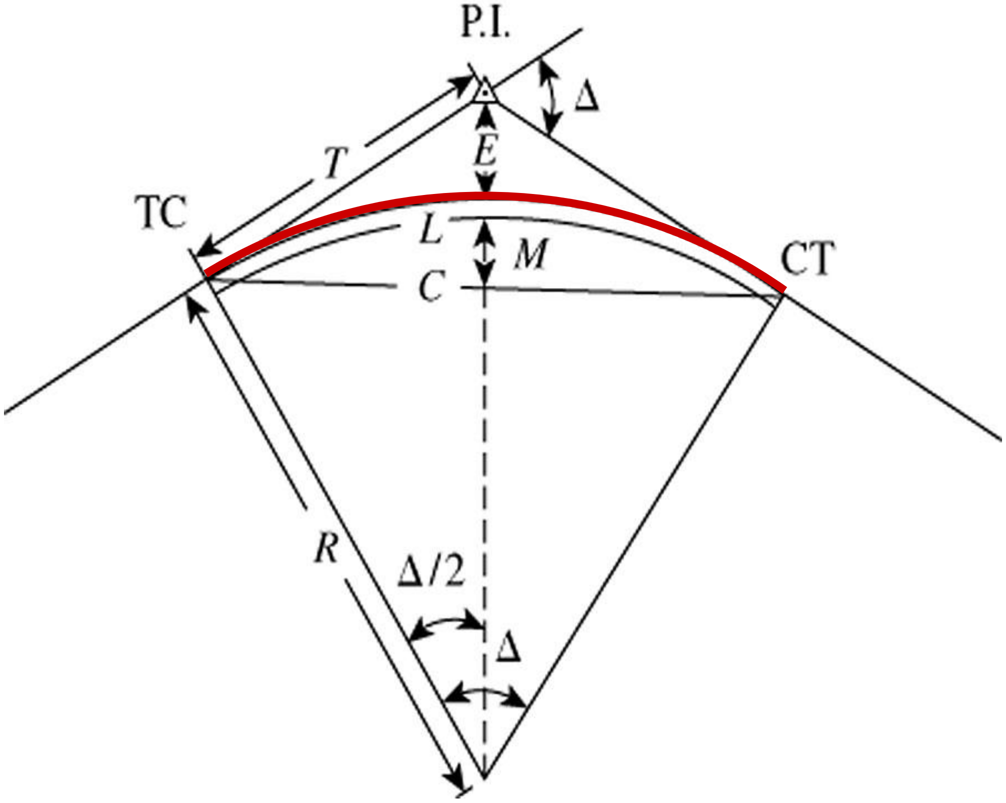
- Is …alignment + cross-section
- Horizontal Alignment consists of:
  - Straight lines
  - Curves:

    Simple circular curves
    - » ***Compound Curves***
    - » ***Reverse Curves***
    - » ***Transitional Spirals***

❑ Considerations

➢ A proper relation should be established between the **design speed** and **curvature** and their joint relations with **super elevation** and **side friction. drainage**

Simple Circular Curves - Terms



Δ=deflection angle
L=Length of Curve
C=Chord Length
R=Radius of Curvature
M=Middle Ordinate
E=External Distance
T=Length of Tangent

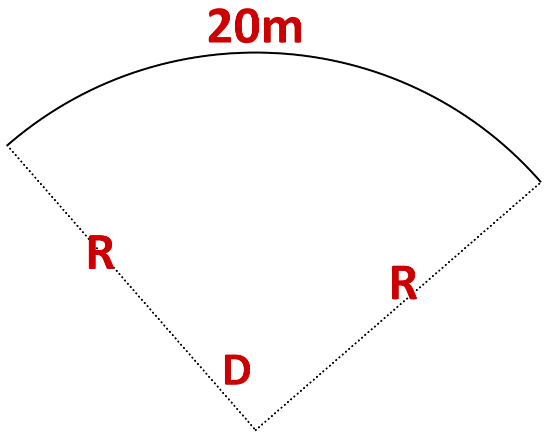
P.I.=Point of Intersection
TC=Tangent to Circle
CT=Circle to Tangent

Degree of Curvature

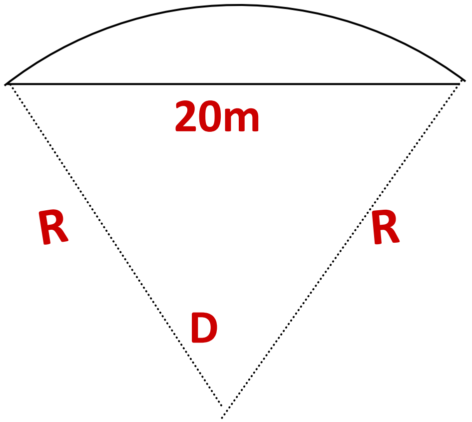
Arc Definition

$$\frac{20}{D} = \frac{2\pi R}{360}$$

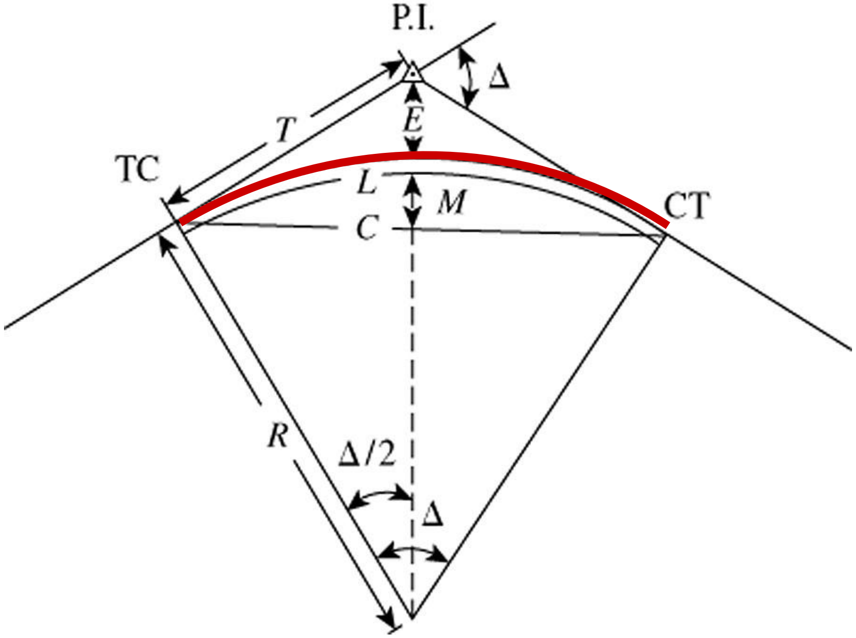
$$D = \frac{1145.92}{R}$$



Chord Definition



Relations



$$T = R\tan(\Delta/2)$$

$$C = 2R\sin(\Delta/2)$$

$$L = R\Delta$$

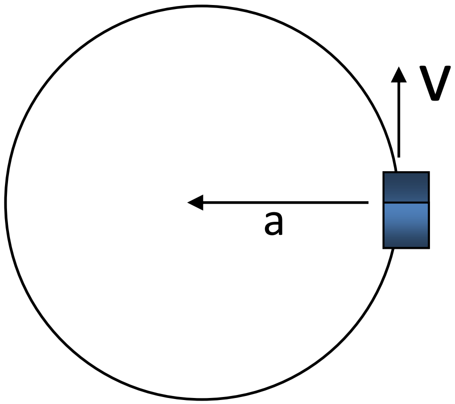
$$E = R[\sec(\Delta/2) - 1]$$

$$M = R[1 - \cos(\Delta/2)]$$

Cont…

a=radial acceleration; m=mass of vehicle; V=speed of vehicle; R=Radius of curvature; F=Frictional Resistance; R'=Reaction

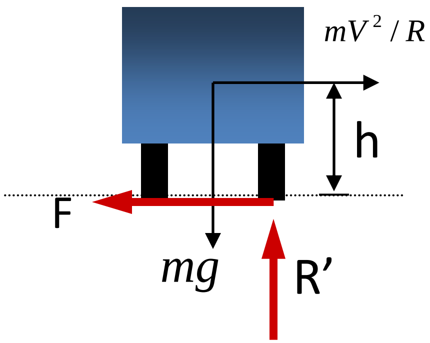
When road has no camber and the VEH is on the verge of overturning



$$R' = mg$$

$$F = mV^2 / R$$ coefficient of friction

$$\mu = F / R'$$



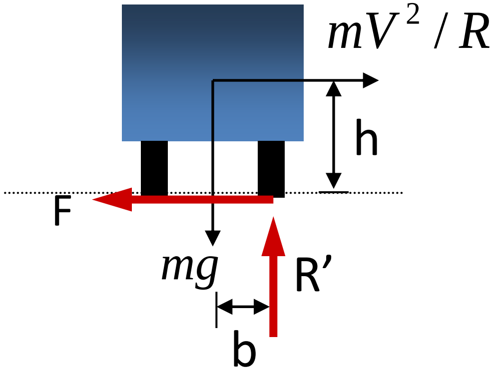
Stability of a VEH

To avoid overturning

$$mV^2h/R < mgb \Rightarrow V^2h/R < gb$$

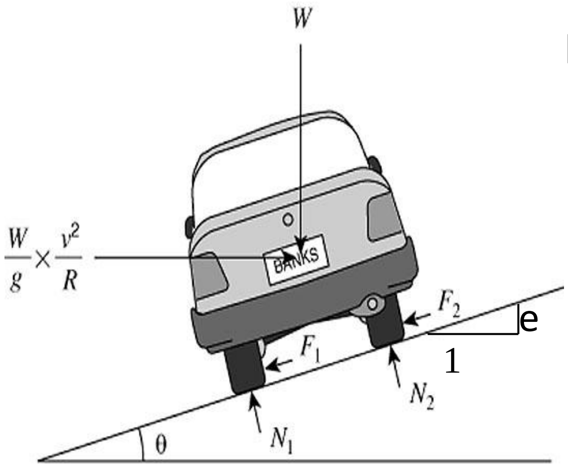
To avoid side slip

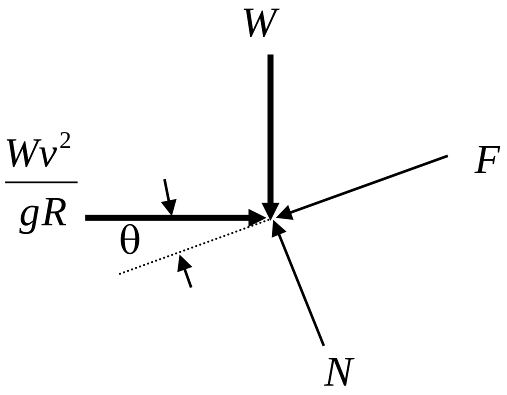
$$mV^2/R < \mu mg \Rightarrow V^2/R < \mu g$$



Stability on Super-elevated Surface

Forces & Equilibrium





Resolving the Forces // and ⊥to the road

(// to the road)

(⊥ to the road)

$$F + WSin\theta = \frac{Wv^2}{gR}Cos\theta$$

$$WCos\theta + \frac{Wv^2}{gR}Sin\theta = N$$

Frictional force, F=μN

Relations (cont.)

$$\mu N = \frac{Wv^2}{gR} Cos\theta - WSin\theta$$

$$\mu\left[\frac{Wv^2}{gR} Sin\theta + WCos\theta\right] = \frac{Wv^2}{gR} Cos\theta - WSin\theta$$

$$Sin\theta\left[\frac{\mu v^2}{gR} + 1\right] = Cos\theta\left[\frac{v^2}{gR} - \mu\right]$$

$$Tan\theta = \frac{\frac{v^2}{gR} - \mu}{\frac{\mu v^2}{gR} + 1}$$

But the term $\frac{\mu v^2}{gR}$ has a very small value and could be ignored for all practical purposes. Check using typical values like V=50km/hr; μ=0.16; and R=100m.

Relations (cont.)

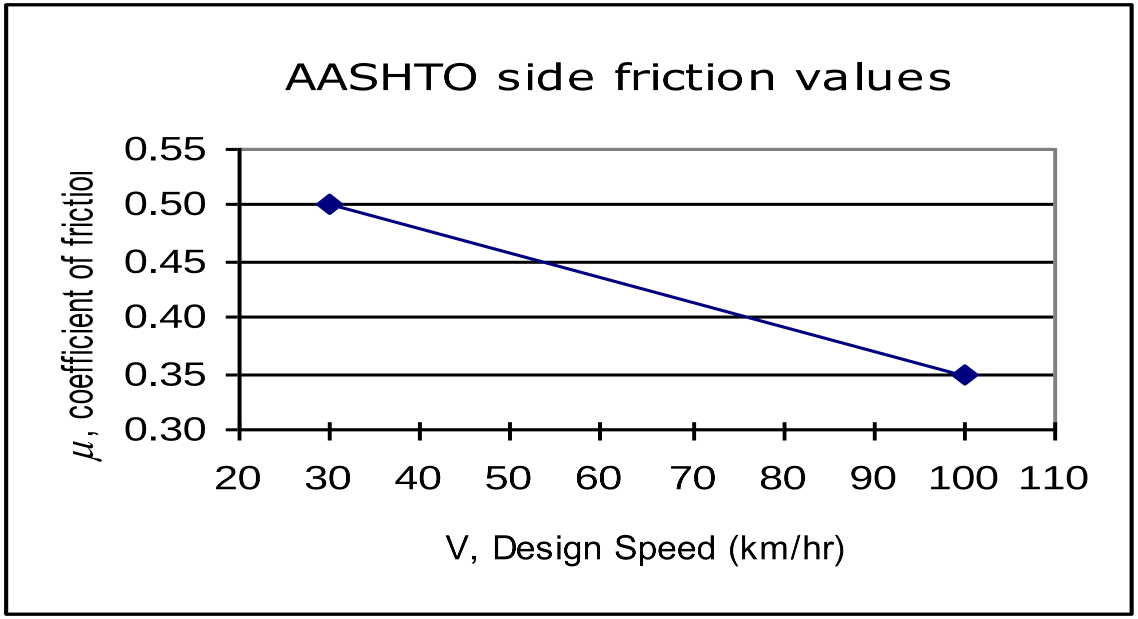
$$Thus,\ Tan\theta = \frac{v^2}{gR} - \mu = e$$

$$\Rightarrow e + \mu = \frac{v^2}{gR} = \frac{(V/3.6)^2}{9.81R} = \frac{V^2}{127R}$$

V=Km/hr
R=m
e=m/m
μ=dimensionless

Safe Side Friction Factor, μ

- μ is low for high speed design than for high speed design



Super-elevation rate, e

- Is the raising of the outer edge of the road along a curve in-order to counteract the effect of radial centrifugal force in combination with the friction between the surface and tyres developed in the lateral direction
- Maximum value is controlled by:
  - Climatic conditions: frequency & amount of snow/icing
  - Terrain condition: flat vs. mountainous
  - Area type: rural vs. urban
  - Frequency of very slow moving vehicles
- 0.1m/m is a logical maximum super-elevation
- Minimum super-elevation rate is determined by drainage requirements
- UK e_{max}: 0.07 (rural) & 0.05 (urban)

Maximum Degree of Curvature

- minimum radius for safety (veh. stability)
- Limiting value for a given design speed (given e_{max} & μ_{max})

$$R_{\min} = \frac{V^2}{127(e+\mu)}$$

- The respective maximum Degree of Curvature is:

- Sharper Curve might justify use of $e > e_{max}$ or a higher dependence on tyre friction or both

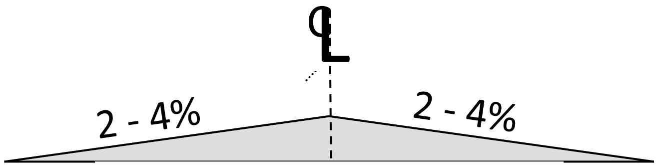
$$D\max = \frac{1145.92}{R_{\min}} = \frac{1145.92}{V^2/127(e+\mu)} = \frac{143240(e+\mu)}{V^2}$$

Application of Super-elevation

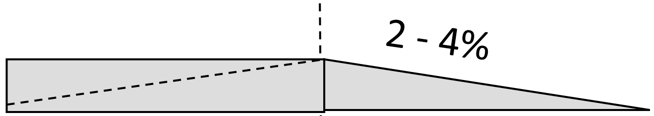
Is done in two stages:

1. Neutralizing the camber of the road gradually, bringing it in to a straight line slope
2. Increasing the slope gradually until design super-elevation is attained

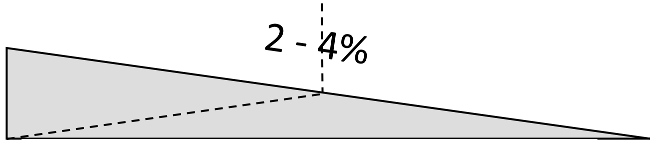
Application of S. E. 2



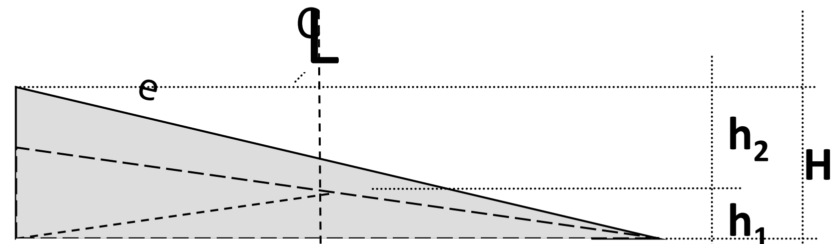
Normal Cross-section



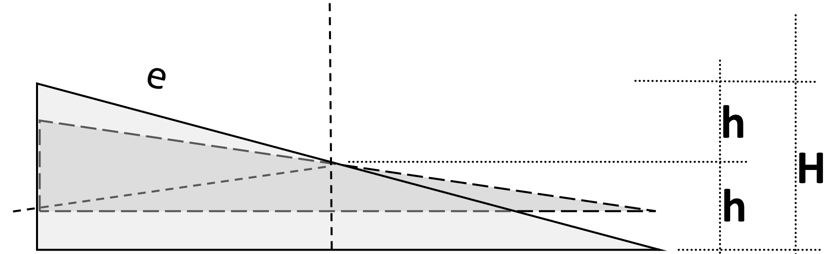
Complete elimination of crown



X-section becomes a straight fall from one side to another



Rotation about the crown



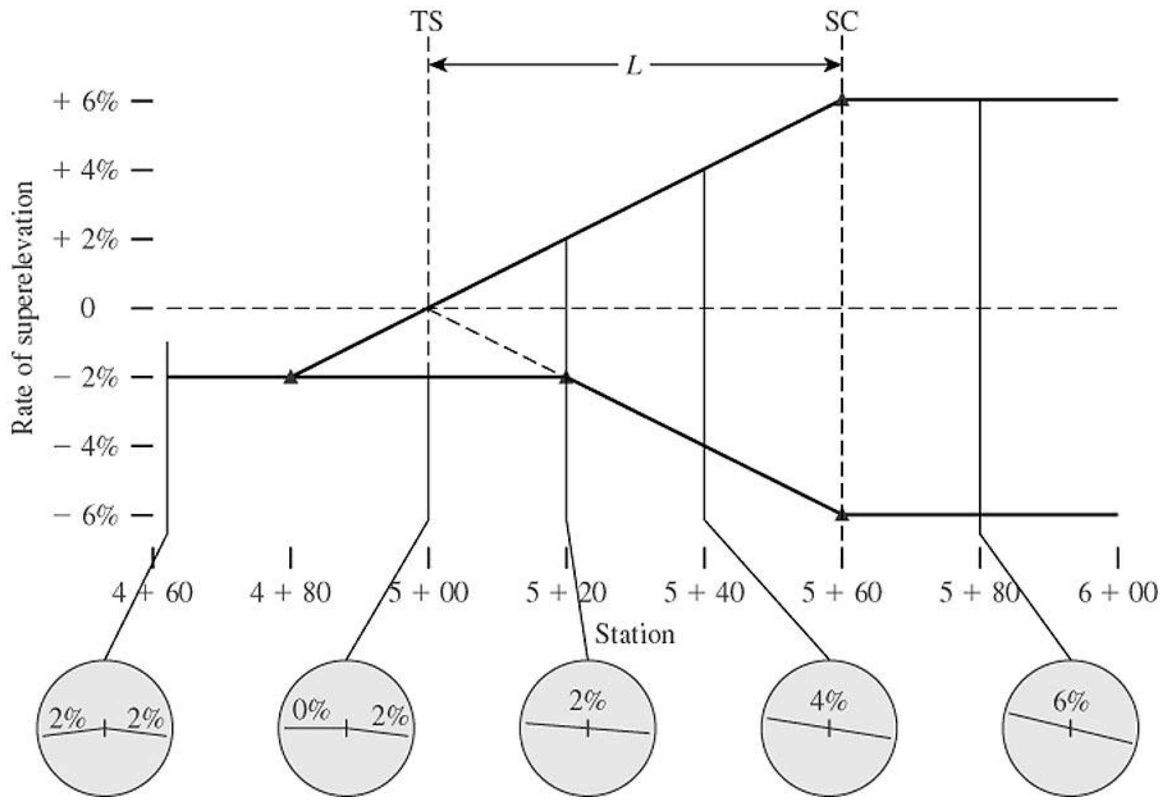
Rotation about the inner edge

Where: H=ew

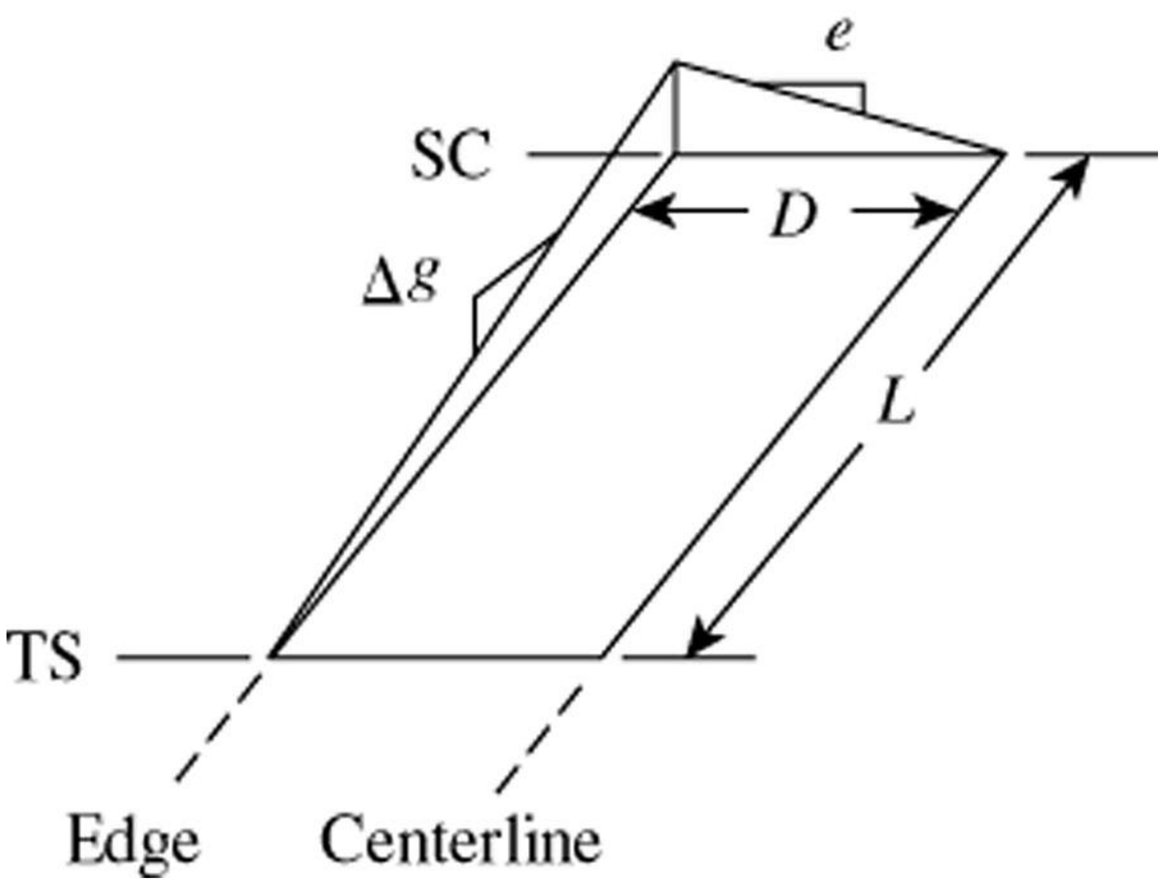
w=width of roadway

Application of S. E. 3

(curve with transition spirals)



Application of S. E. 4

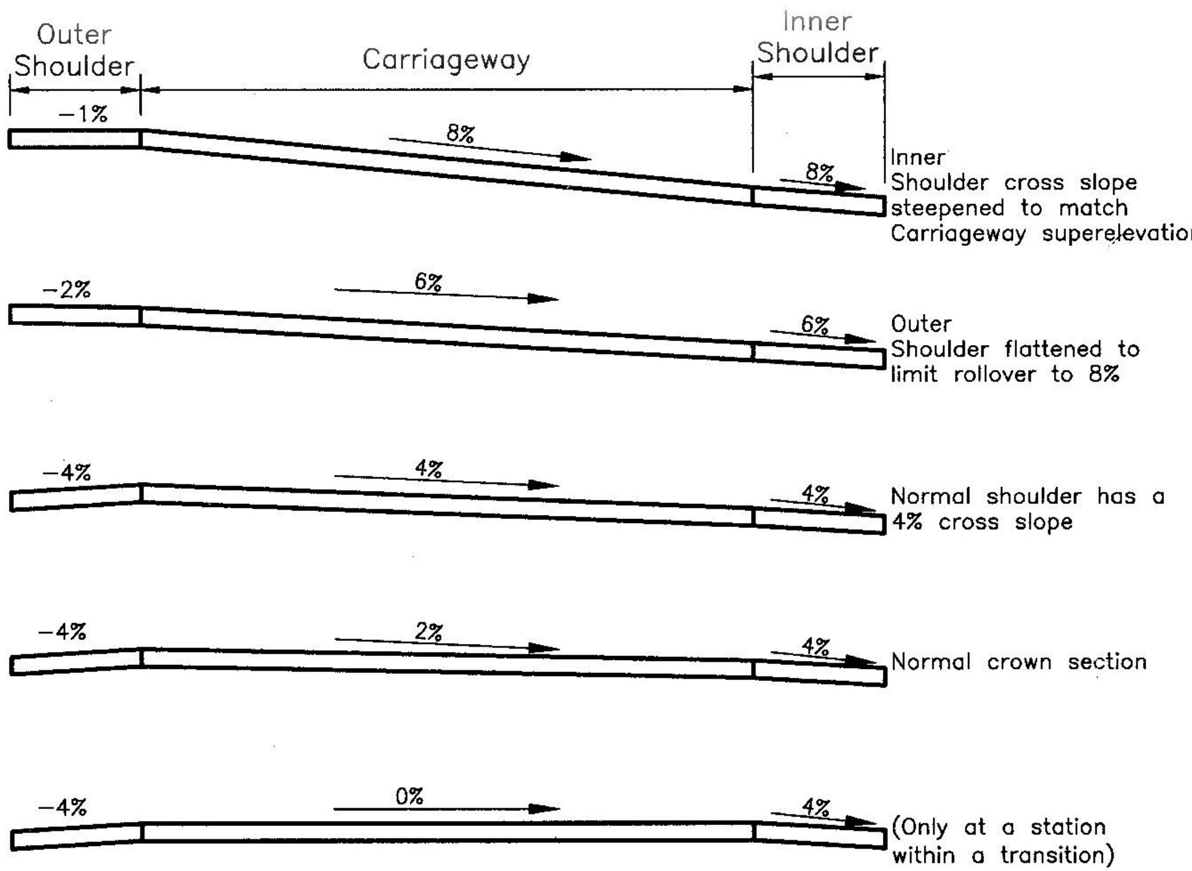


Application of Super-Elevation 5

(for curves with no spirals)

- Super-elevation is started 1/2 to 1/3 into the tangent with the balance being applied with in the curve

Shoulder Super-elevation



Transition Curves

a.k.a. spirals these are curves which provide a gradual change in curvature from tangent to a circular path

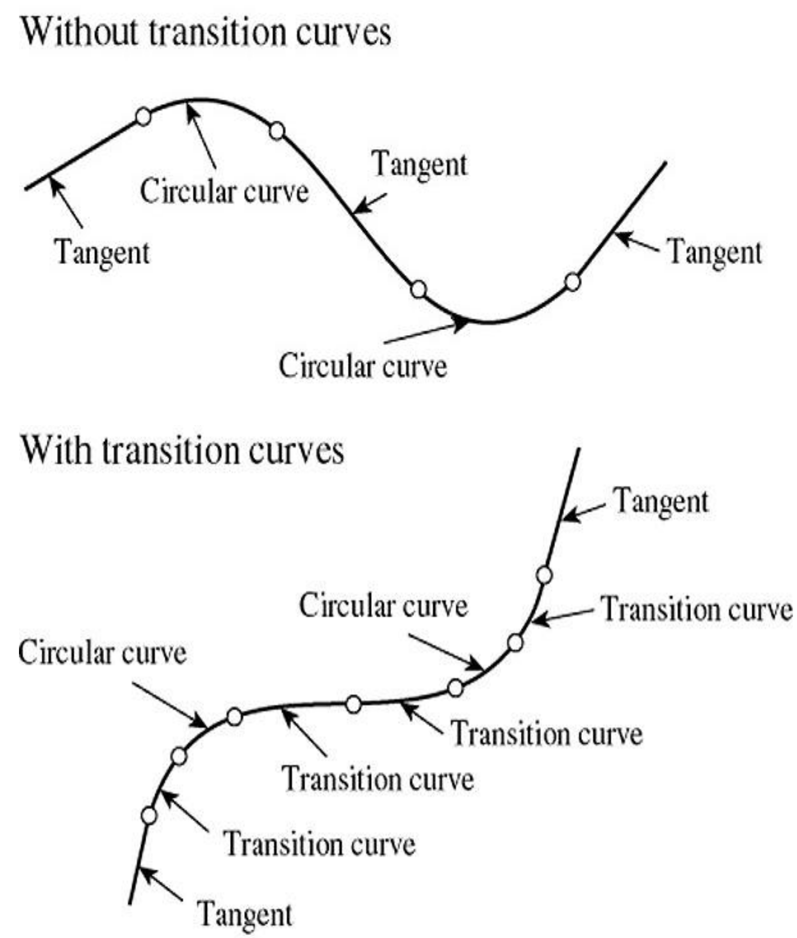
Advantages:

•Provides an easy-to-follow path so that centrifugal force increases and decreases gradually; lesser danger of overturning/ side-slipping

•Vehicle could keep to the middle of lane while traversing a curve

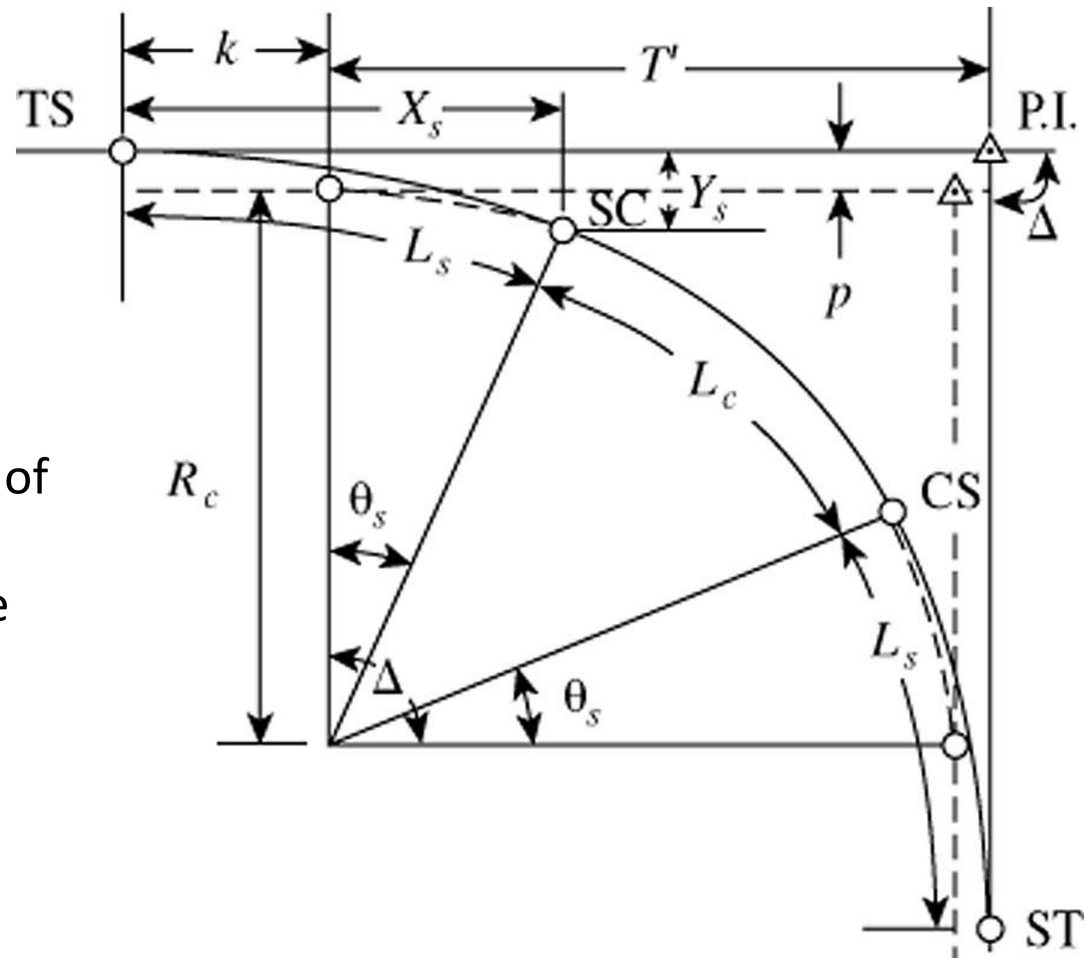
•Is convenient for the application of super-elevation

•Improved visual appearance, no “kinks”



Transition Curves - Geometry

PI: Point of Intersection
TS: Tangent to spiral
SC: Spiral to Circle
CS: Circle to Spiral
ST: Spiral to tangent
L_s: Total length of spiral
L_c: Length of circular curve
θ_s: Central angle of spiral arc of length L_s
Δ=total deflection angle of the curve
Y_s=tangent offset at SC
X_s=
K=abscissa of shifted PC with reference to TS



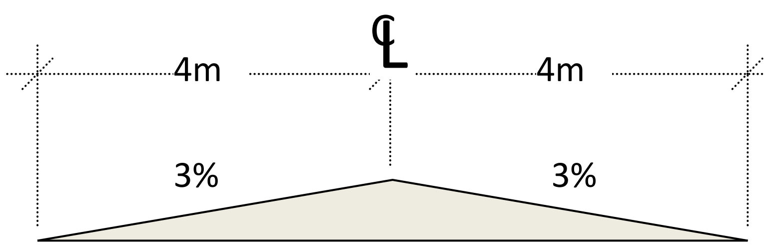
Length of Transition Curves

1. Length required for super-elevation runoff
   - Super-elevation runoff: length of highway needed to accomplish the change in cross slope from a normal crown section to a fully super-elevated section (or, vice versa)
   - The rate of raising the outer edge above the centre line should be:

Design Speed (kph)	Ratio V:H
80	1:200
64	1:175
48	1:150
32	1:125

Example

Given: A 2-lane road, each with width 4m, crown slope = 3%, design speed = 80kph, rate of super-elevation, e=0.1m/m. Find the length of transition curve if full super-elevation is going to be achieved by rotation about the inner edge of the carriage way



Length required for super-elevation runoff

2. Length required for driver comfort
   - Rate of change of radial acceleration mustn't exceed a certain value which is acceptable to drivers

$$P = \frac{mv^2}{R} \Rightarrow a_r = \frac{v^2}{R}$$

$$v \approx constant$$

$$\Rightarrow rate\ of\ change\ of\ a_r\ \alpha\ 1/rate\ of\ change\ of\ R$$

$$\Rightarrow faster\ change\ in\ R \Rightarrow faster\ change\ in\ radial\ force$$

$$\Rightarrow greater\ passenger\ discomfort$$

   - **Transition curve must, therefore, be long enough to ensure that the radius can be changed at a slow rate**

Cont…

$$\Delta a_{r_{(from TS-SC)}} = v^2 / R$$

$$\Delta t_{(from TS-SC)} = ls / v$$

$$rate\ of\ change\ of\ radial\ acc., C = \frac{\Delta a_r}{\Delta t} = \frac{v^2/R}{ls/v} = \frac{v^3}{lsR}$$

$$ls = \frac{v^3}{cR}$$

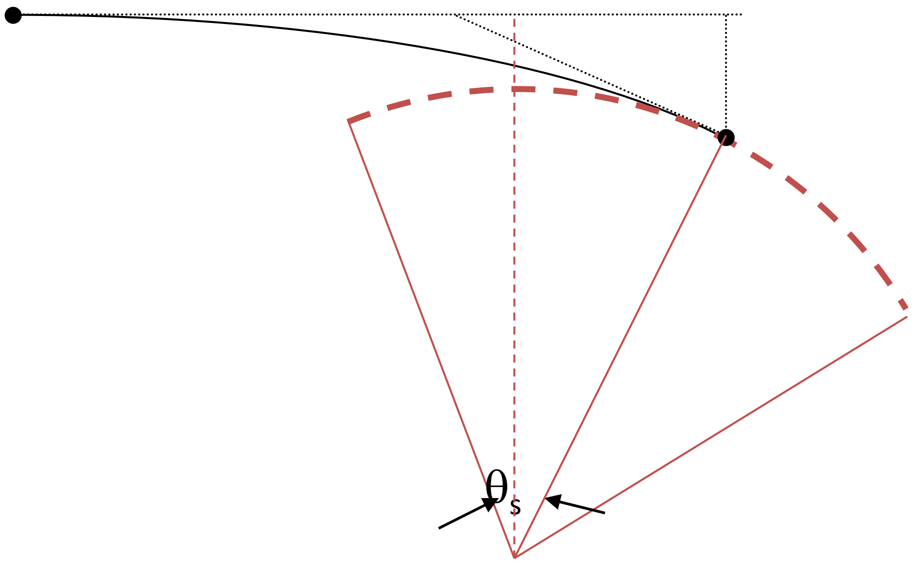
$$ls = \frac{(0.28V)^3}{cR} = \frac{(V)^3}{46.66cR}$$

The value of c lie in the range 0.2 to 0.6m/sec^3; c=0.3m/sec^3 is often used.

Example

Given design speed=50kph, e=0.10m/m, c=0.3m/sec3, and n=0.15; determine the length of the transition curve

Length of Transition Curves



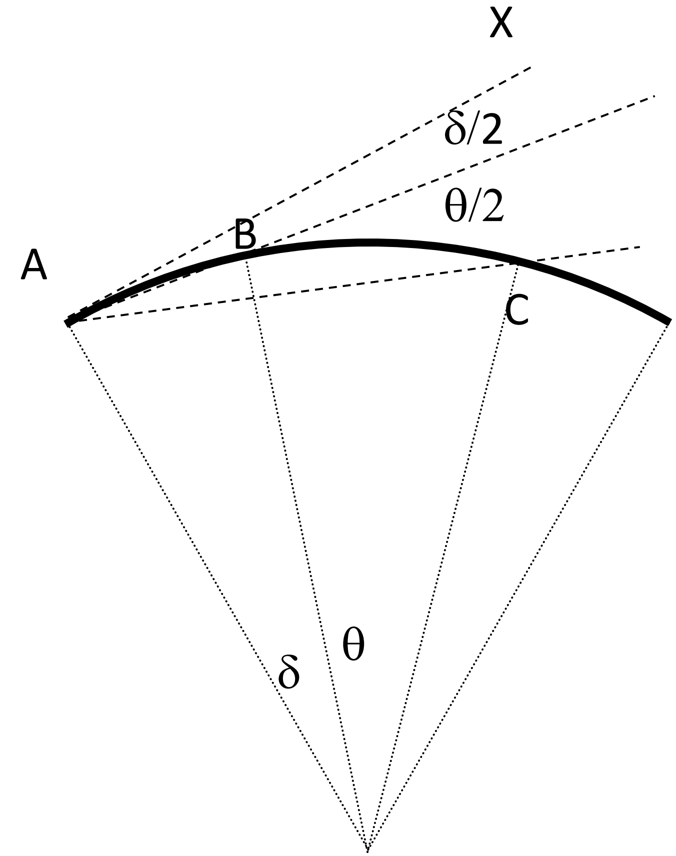
Setting out a Simple Horizontal Curve by deflection angles

To locate B

- <XAB=$\delta/2$
- Measure AB from A
- Align B with the theodolite

To Locate C

- <XAC=$\delta/2 + \theta/2$
- Measure AC from A
- Align C with the theodolite



Widening of Highway Curves

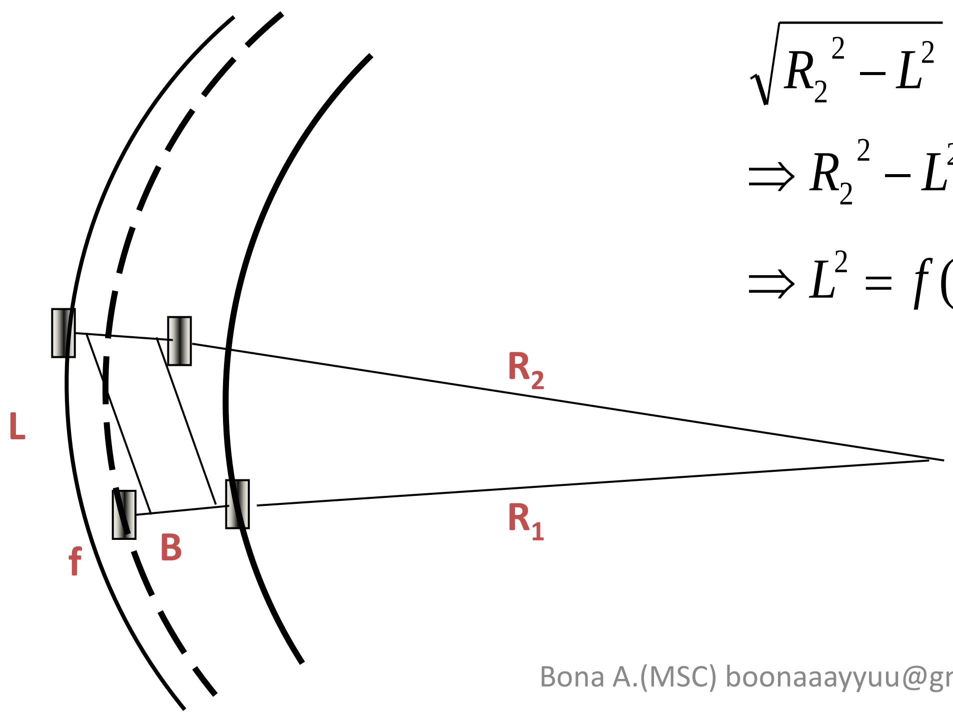
Need

- Rear wheels don’t follow front wheels,
- Trailers fitted on trucks, don’t follow path of trucks wheels
- To have adequate sight-distances
- Drivers tend to keep greater clearances with vehicles coming from the opposite direction and might thus move out of a lane when traversing a curve

Amount of Extra Widening

Let

R_1 =radius of inner rear-wheel on a curved truck (m)
R_2 =radius of outer front-wheel (m)
B=width of vehicle
f=widening (m)
L=Length of vehicle (m)



$$R_1 + B = \sqrt{R_2^{\,2} - L^2} = R_2 - f$$

$$\sqrt{R_2^{\,2} - L^2} = R_2 - f$$

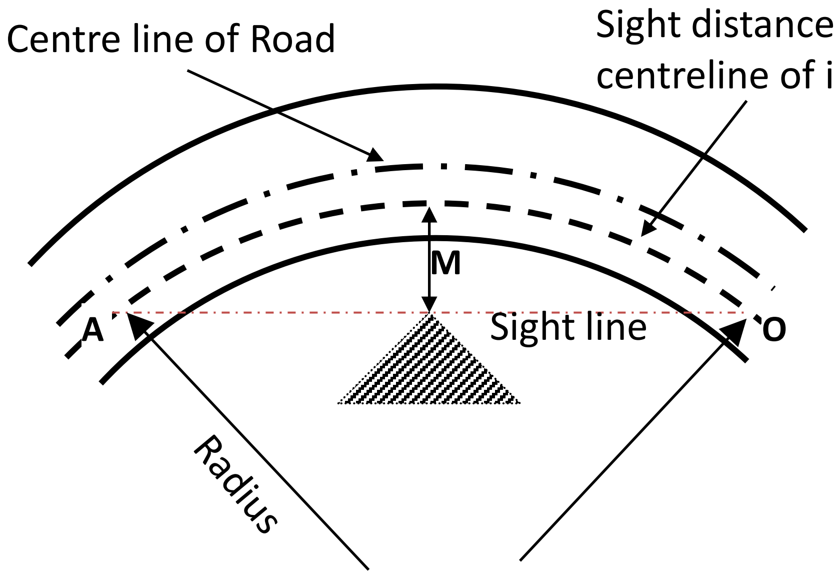
$$\Rightarrow R_2^{\,2} - L^2 = (R_2 - f)^2 = R_2^{\,2} - 2R_2 f + f^2$$

$$\Rightarrow L^2 = f(2R_2 - f) \Rightarrow f = \frac{L^2}{2R_2 - f} \approx \frac{L^2}{2R_2}$$

Empirical formulas for Amt. of Widening

- Vorshell $$w = 0.07D + 0.462\sqrt{D}$$
- Barnett $$w = n\left(R - \sqrt{R^2 - L^2}\right) + \frac{V}{\sqrt{R}}$$
- Hickerson $$w = 1 + 0.1D$$

Sight Distance on Horizontal Curves



Considering a vehicle at A and an object at O, sight distance should at-least equal to safe stopping distance.

If the angle subtended at the centre of the circle is 2θ, then

$$SD = 2R\theta\pi/180$$

$$\theta = 57.3S/2R,$$

$$\frac{R-m}{R} = Cos\theta = Cos(57.3S/2R)$$

$$m = R(1 - Cos(28.65/R))$$

Widening - Methods

- On a simple curve (*i.e. with no spirals*) widening should be applied on the inside edge of a pavement only. For curves with spirals, widening could be applied on the inside (only) or could be equally divided b/n the inside and outside
- Widening should be attained gradually over the i.e. runoff length but shorter lengths are sometimes used (*usually this length is 30 – 60m*).
- Widening is costly and very little is gained from a small amount of widening.

Vertical Alignment

Vertical curves

- Connect roadway grades (tangents)
- Grade (rise over run)
  - 10% grade increases 10’ vertically for every 100’ horizontal
- Ascending grade:
  - Frequency of collisions increases significantly when vehicles traveling more than *10 mph below* the average traffic speed are present in the traffic stream

Descending Grades

- Problem is increased speeds and *loss of control for heavy trucks*
- Runaway vehicle ramps are often designed and included at critical locations along the grade
- Ramps placed before each turn that cannot be negotiated at runaway speeds.
- Ramps should also be placed along straight stretches of roadway, wherever unreasonable speeds might be obtained
- Ramps located on the right side of the road when possible

Maximum Grades

- Passenger vehicles can *easily negotiate 4 to 5% grade without appreciable loss in speed*
- *Upgrades:* trucks average 7% decrease in speed
- *Downgrades*: trucks average speed increase 5%
- *Parabolic shape*

VPI, VPC, VPT, +/- grade, L

Types of crest and sag curves

Cont…

- Crest – stopping, or passing sight distance controls
- Sag – headlight/SSD distance, comfort, drainage and appearance control
- Green Book vertical curves defined by K = L/A = length of vertical curve/difference in grades (in percent) = length to change one percent in grade

Vertical Curve Equations

Parabola

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

Where:

y = roadway elevation at distance x

x = distance from beginning of vertical curve

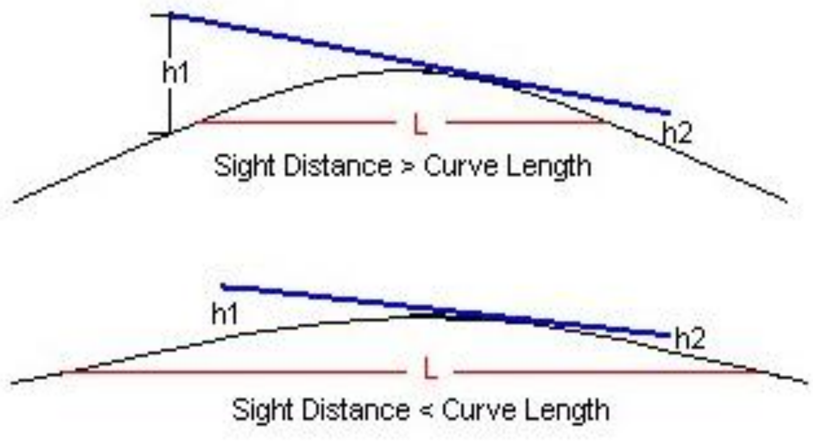
$$a = \frac{G2 - G1}{L}$$

b = G1

c = elevation of PVC

Vertical Curve AASHTO Controls (Crest)

- Minimum length must provide stopping sight distance (SSD) or "S" in equations
- Two situations (both assume h_1=3.5' and h_2=2.0')



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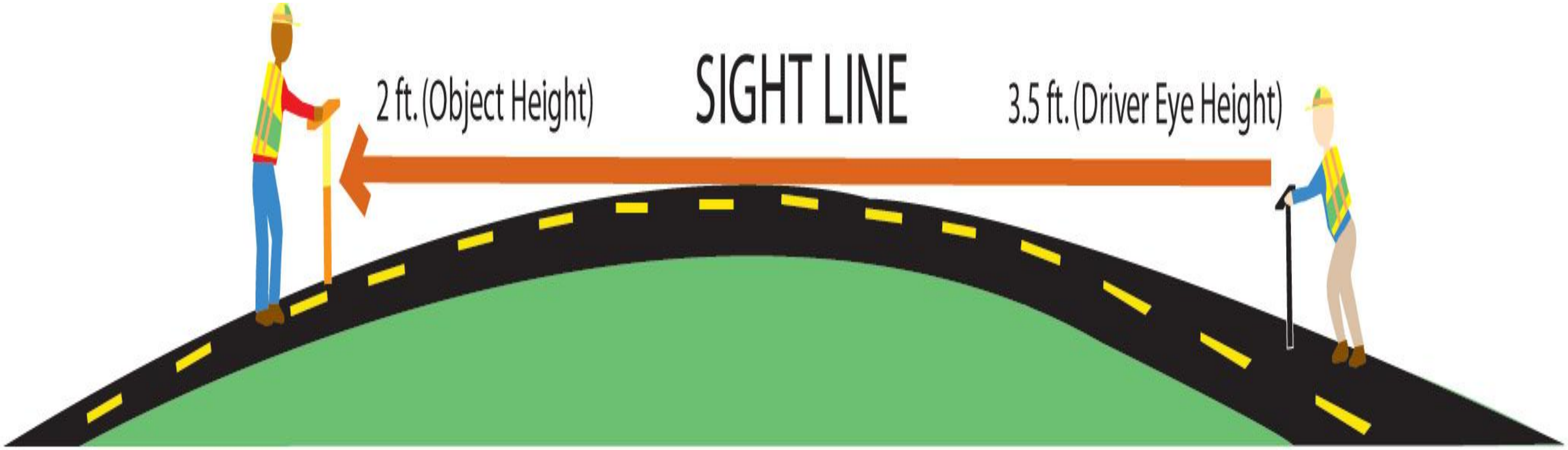


Cont…

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

Note: for passing sight distance, use 2800 instead of 2158

Vertical Alignment

- Consists of straight sections of the highway known as grades, or tangents, connected by vertical curves.
- The design involves the selection of suitable GRADES for the tangent sections and the design of the VERTICAL CURVES.
- The topography of the area through which the road traverses has a significant impact on the design of the vertical alignment.

GRADES

- Effect of grade is more pronounced on Heavy Vehicles than on Passenger Cars
- *Maximum Grade on a highway should be carefully selected based on the design speed and design vehicle*.
- ***grades of 4 to 5 %*** $\Rightarrow$ little or no effect on passenger cars, except for those with high weight/horsepower ratios,
- ***grade > 5%*** $\Rightarrow$speed of passenger cars decrease on upgrades and increase on downgrades.
- ***truck speeds may increase up to 5 percent*** on downgrades and decrease by 7 percent on upgrades

Maximum Grade

Design Speed	Maximum Grade
110 kph	5%
50 kph	7-12%
60 to 100 kph	Intermediate
Very Important highways	7-8%
Short grades less than 150m & one-way downgrades	1% steeper
Low volume highways	2% steeper

Minimum Grade

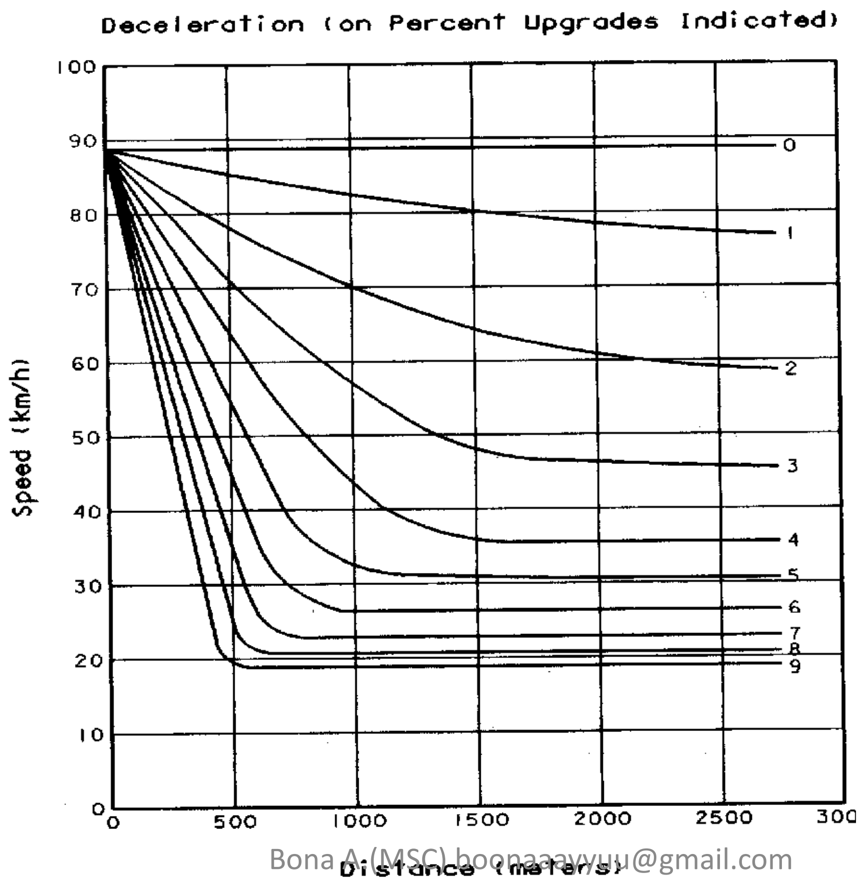
- depend on the drainage conditions of the highway
- zero-percent grades may be used on uncurbed pavements with adequate cross slopes to laterally drain the surface water
- for curbed pavements, however, a longitudinal grade should be provided to facilitate the longitudinal flow of the surface water
- a minimum grade of 0.5% is usually used; it may reduced to 0.3% on high-type pavement constructed on suitably crowned, firm ground.

Critical Length of Grade

- indicates the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed
- For a given grade, lengths less than critical result in acceptable operation in the desired range of speeds.
- ***to maintain LOS on grades longer than critical***
  - *change in location to reduce grades*
  - *addition of extra lanes (climbing or crawler lanes):* data for critical lengths of grade are used with other pertinent considerations (such as traffic volume in relation to capacity, % heavies) to determine where added lanes are warranted.
- To establish design values for critical lengths of grade data or assumptions are needed on the following:
  - *Size and power of representative truck or truck combination to be used as a design vehicle*
  - *Speed at entrance to critical length grade*
  - *Minimum speed on the grade below which interference to following vehicles is considered unreasonable*

Effect of Grade

Speed-distance curves for a typical heavy truck of 180kg/kw for deceleration on upgrades

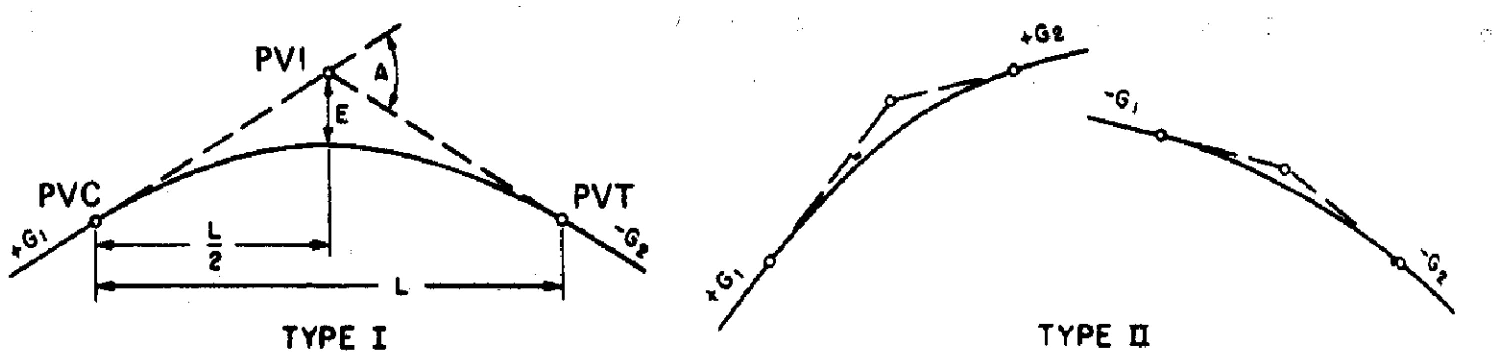


Vertical Curves

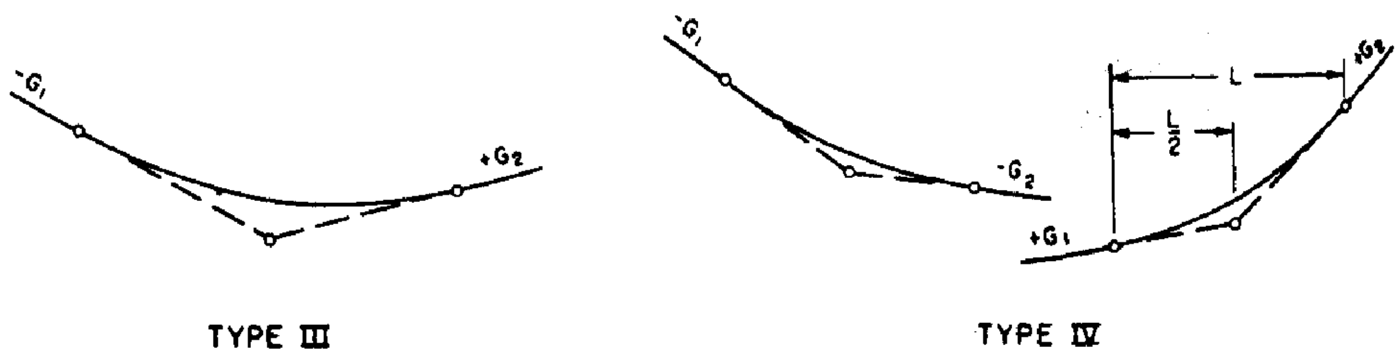
- are parabolic curves used to provide a gradual change from one tangent grade to another so that vehicles may run smoothly as they traverse the highway.
- Are of two types
  - Sag Vertical Curves
  - Crest Vertical Curves
- Design Criteria for vertical curves
  - Provision of minimum stopping sight distance
  - Adequate drainage
  - Comfortable in operation
  - Pleasant appearance

The first criterion is the only criterion associated with crest vertical curves, whereas all four criteria are associated with sag vertical curves.

Types of Vertical Curves



(a) Crest vertical curves



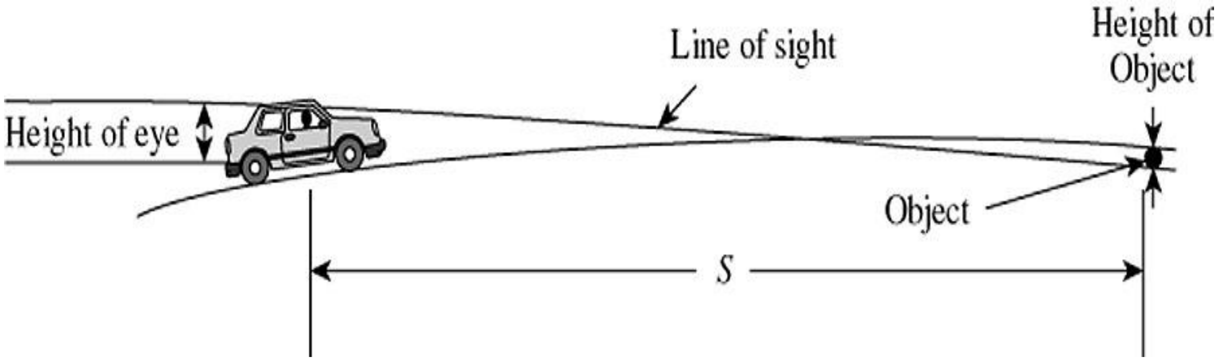
(b) Sag vertical curves

Crest Vertical Curves

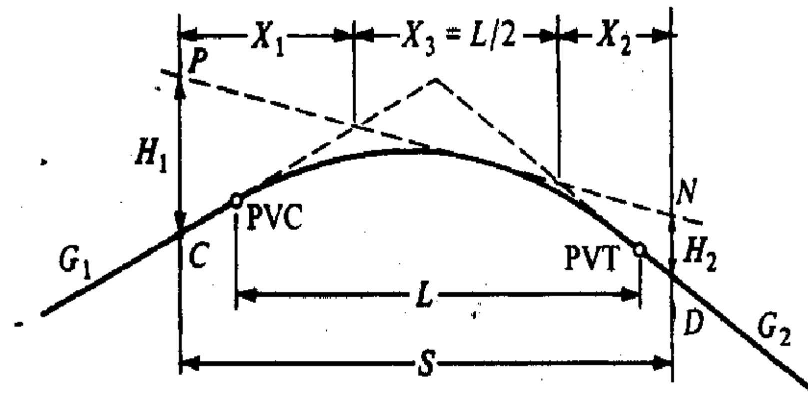
- Minimum length of the vertical curve (L) is determined by sight distance (SD) requirements
- That length is generally are satisfactory from the standpoint of safety, comfort, and appearance.
- Derivation is done for the two cases of:
  - **SD > L**
  - **SD < L**

Crest Vert. Curves

minimum length when S>L



Vehicle on the grade at C
H_1 height of the driver's eye at C
H_2 height of an object at D
PN is line of sight, and
S is the sight distance



Note that the line of sight is not necessarily horizontal, but in calculating the sight distance, the horizontal projection is considered

Crest Vert. Curves

Min. length – Derivation (S>L)

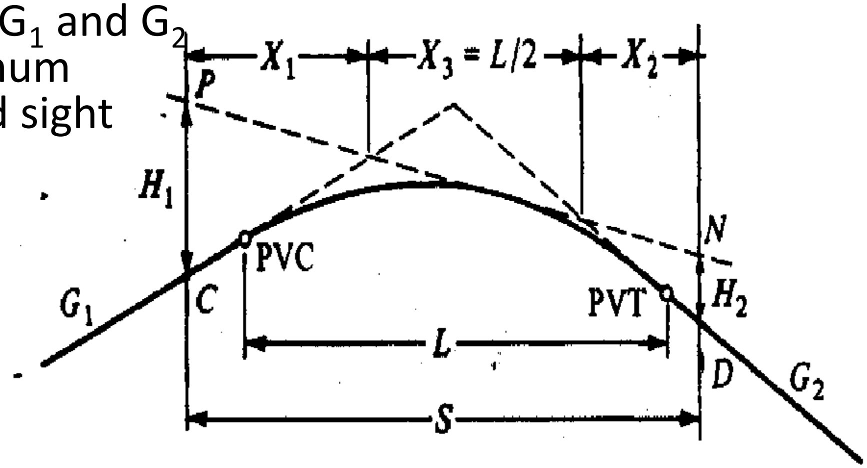
From the properties of the parabola,

$X_3 = L/2$

The sight distance S is then given as

$S = X_1 + L/2 + X_2$

X_1 and X_2 can be found in terms of the grades G_1 and G_2 and their algebraic difference *A*. The minimum length of the vertical curve for the required sight distance is obtained as



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

where,

L = length of vertical curve, m

S = sight distance, m

A = algebraic difference in grades, %

H_1 = height of eye above roadway surface, m

H_2 = height of object above roadway surface, m

Cont…

- When the height of eye and the height of object are 1070 mm and 150 mm, respectively, as used for stopping sight distance, the length of the vertical curve is,

$$L = 2S - \frac{404}{A}$$

Crest Vert. Curves

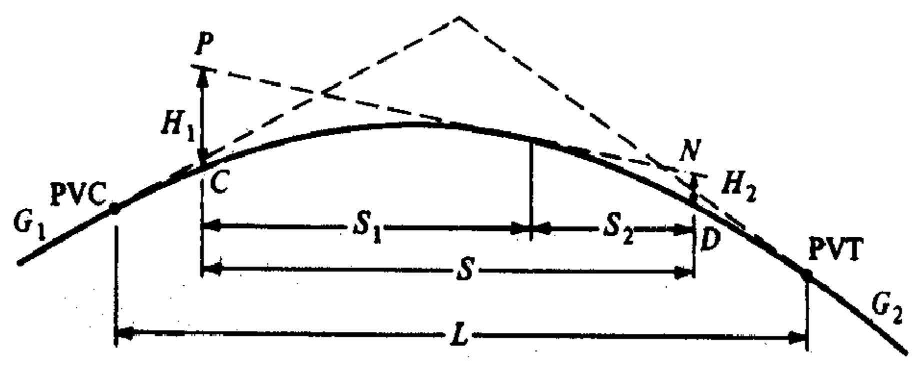
Min. length – Derivation (S<L)

Similarly:

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

Substituting 1070 mm for H_1 and 150 mm for H_2 gives

$$L = \frac{AS^2}{404}$$



Design for Passing sight distance

differ from those for stopping sight distance because of the different height criterion (i.e. 1300 mm height of object) results in the following specific formulas with the same terms as above:

When $S > L$,

$$L = 2S - \frac{946}{A}$$

When $S < L$,

$$L = \frac{AS^2}{946}$$

Sag Vertical Curves

Design Criteria:

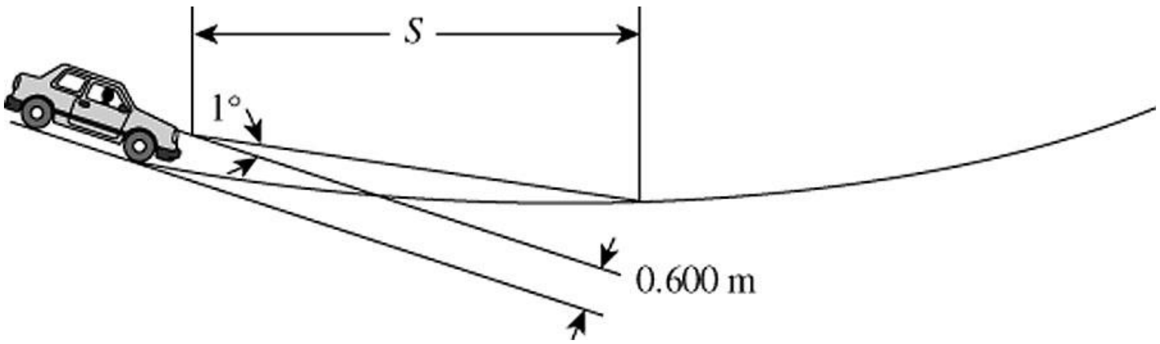
1. Headlight sight distance
2. Rider Comfort
3. Drainage Control
4. Aesthetics (rule of thumb)

Headlight Sight Distance, S

Height of the headlight =600mm

Upward divergence of the light beam = 1^o

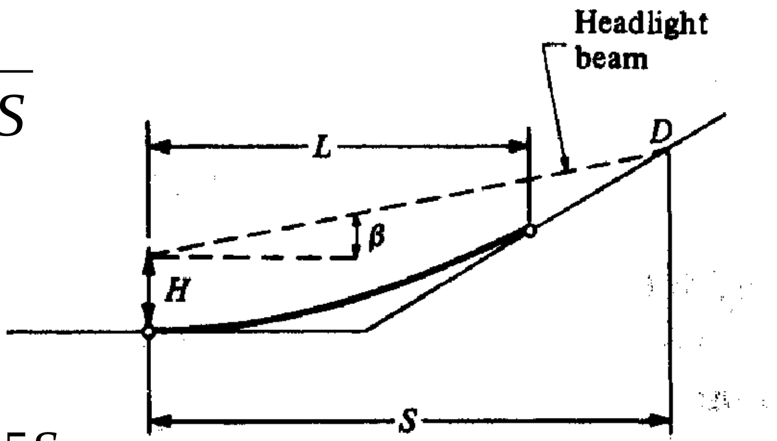
(The upward spread of the light beam provides some additional visible length, but that is generally ignored.)



Length of curve with adequate SD

When S<L:

$$L = \frac{AS^2}{200(0.6 + S\tan\beta)} = \frac{AS^2}{120 + 3.5S}$$



When S>L:

$$L = 2S - \frac{200(0.6 + S\tan\beta)}{A} = 2S - \frac{120 + 3.5S}{A}$$

L=length of curve (m), A=algebraic difference in grade (%), and S=headlight distance (m)

Length of Curve for comfort

- Considers that both the gravitational and centrifugal forces act in combination, resulting in a greater effect than on a crest vertical curve
- Comfort is affected by:
  - weight carried, body suspension of the vehicle, and tire flexibility
  - Measuring Comfort = Difficult!
  - Indicator = radial acceleration is not greater than 0.3 m/s^3
- The general expression for such a criterion is:

$$L = \frac{AV^2}{395}$$

  V is the design speed, km/h.
- Usually this length is about 50 percent of that required to satisfy the headlight sight distance at various design speeds (for normal conditions).

Min. Length for Aesthetics

- Rule of thumb

$$L_{\min} = 30A$$

- Longer curves are necessary for high type of highways to improve appearance.

Max. Length of Curve for drainage

Here the drainage criteria sets a limit on the MAXIMUM length of curve!

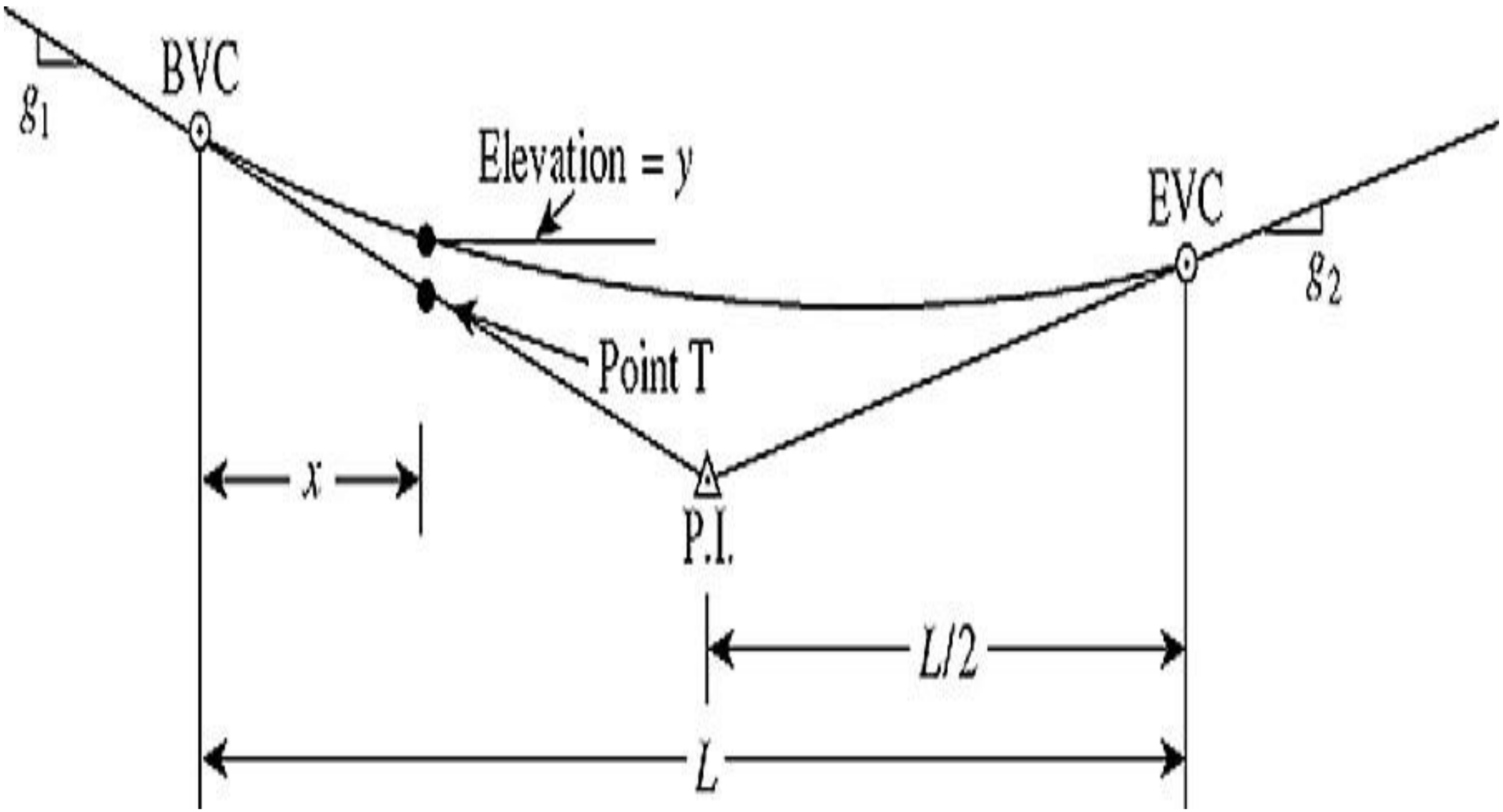
- Long curves would have a relatively flat portion near the bottom of curve
- A min. grade of 0.3% should be provided with in 15m of the level point of the curve
- Max length (drainage) is usually greater than min. length for other criteria up to 100kph and nearly equal to min length for other criteria up to 120kph

Combination of Horizontal and Vertical Alignments

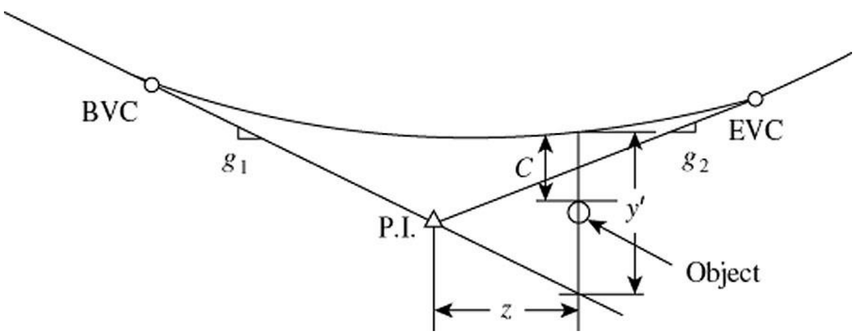
- Horizontal and Vertical Alignments should not be designed independently and should be considered together
- Correcting alignment deficiencies is extremely difficult and costly!
- Phasing of the vertical and horizontal curves of a road implies their coordination so that the line of the road appears to a driver to flow smoothly, avoiding the creation of hazards and visual defects. It is particularly important in the design of high-speed roads on which a driver must be able to anticipate changes in both horizontal and vertical alignment well within the safe stopping distance. It becomes more important with small radius curves than with large.
- Defects may arise if an alignment is mis-phased. Defects may be purely visual and do no more than present the driver with an aesthetically displeasing impression of the road. Such defects often occur on sag curves. When these defects are severe, they may create a psychological obstacle and cause some drivers to reduce speed unnecessarily. In other cases, the defects may endanger the safety of the user by concealing hazards on the road ahead. A sharp bend hidden by a crest curve is an example of this kind of defect.

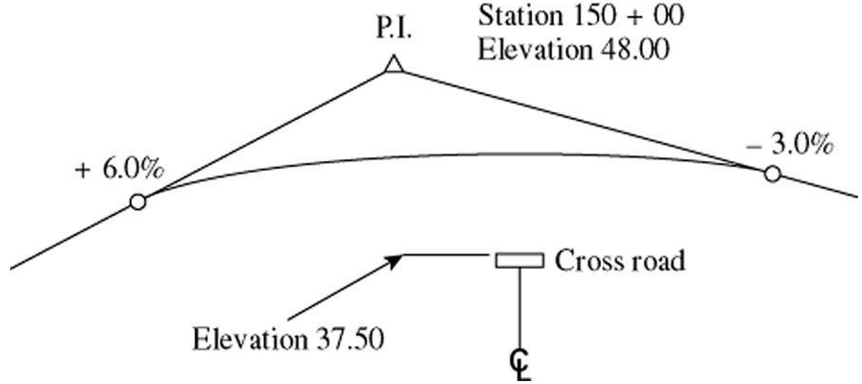
Alignment Defects Due to Mis-phasing

- This refers to the coordination of HA & VA so that the line of the road appears to a driver to flow smoothly, avoiding the creation of hazards and visual defects.
- Is particularly important in the design of high-speed roads on which a driver must be able to anticipate changes in both HA & VA well with in the SSD and on curves with small radius.
- Defects may arise if an alignment is mis-phased. Defects may:
  - *Be purely visual*
  - *Create psychological obstacle and cause some drivers to reduce speed unnecessarily*
  - *Endanger the safety of the user by concealing hazards on the road ahead (e.g. sharp bend hidden by a crest curve)*



BVC
g_1
Elevation = y
EVC
g_2
Point T
x
P.I.
L/2
L


BVC
EVC
g_1
g_2
C
y′
P.I.
Object
z


P.I.
Station 150 + 00
Elevation 48.00
+ 6.0%
– 3.0%
Cross road
Elevation 37.50
℄

Sight Distance

- Basically, it is the distance visible to the driver of a vehicle
- For highway safety, the designer must provide sight distances of sufficient length that drivers can control the operation of their vehicles. They must be able to avoid striking an unexpected object on the traveled way.
- Two-lane highways should also have sufficient sight distance to enable drivers to occupy the opposing traffic lane for passing maneuvers, without risk of accident.
- Two-lane rural highways should generally provide such passing sight distance at frequent intervals and for substantial portions of their length.

Braking Distance

$$D_b(ft) = \frac{u^2(mph)}{30(f \pm G)}$$

D_b = braking distance
u = initial velocity when brakes are applied
f = coefficient of friction
G = grade (decimal)

Assumes a rate of deceleration, driver may brake harder

a = 11.2 ft/sec^2 normal

a = 14.8 ft/sec^2 emergency, use tables from AASHTO

Friction is a function of pavement condition (wet, icy), tire, and roadway surface

Depends on weight, but some assumptions are made to arrive at a standard equation

Stopping sight distance

$$SSD = (0.278)(t)(V) + \frac{V^2}{254f}$$

SSD = Stopping Sight Distance (meter)
= Dist. traveled during perception/reaction time + Braking Dist.
t = driver reaction time, generally taken to be 2.5 seconds
V = initial speed (km/h)
f = coefficient of friction between tires and roadway

Effect of Grade of SSD

- On grade, the braking distance formula is modified to

$$d = \frac{V^2}{254(f \pm G)}$$

Where G=percent of grade divided by 100.

Note:

1. Safe SSD on upgrades is shorter than on downgrades
2. Min. SD should be adjusted where steep grades and high speed occur in combination

Cont…

- g = acceleration of gravity
- a = acceleration of vehicle
- u = initial velocity when brakes are applied
- Db = braking distance
- γ = angle of incline
- f = coefficient of friction
- G = grade (decimal)

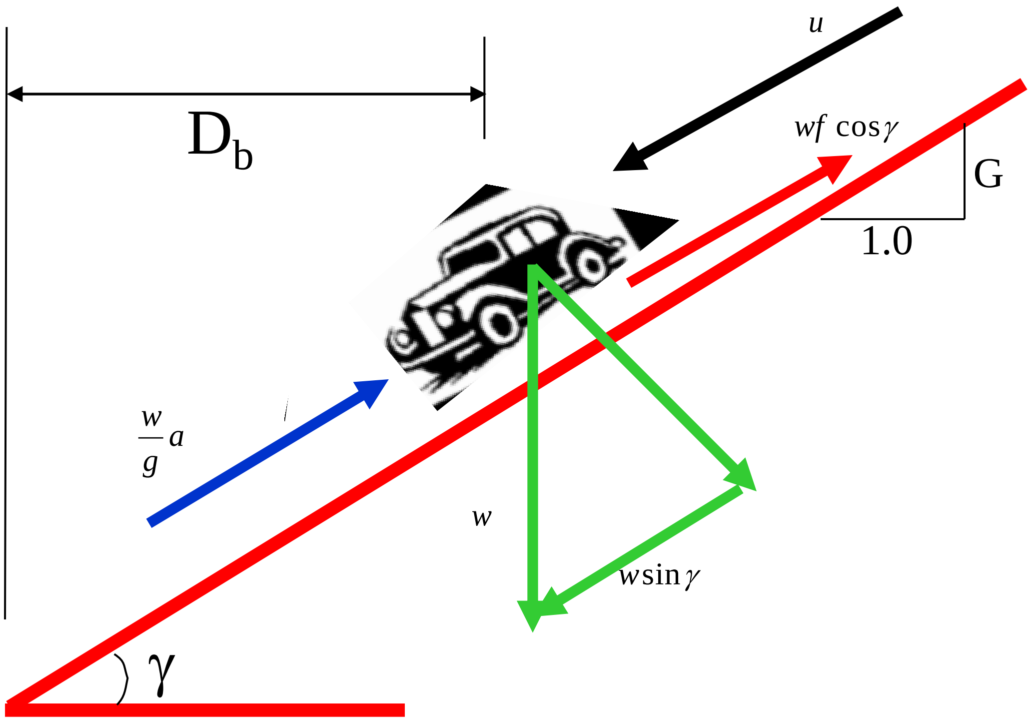
$$w\sin\gamma - wf\cos\gamma = \frac{w}{g}a$$

$$a = \frac{-u^2}{2x}$$

$$D_b = x\cos\gamma$$

$$D_b(ft) = \frac{u^2(mph)}{30(f \pm G)}$$

Stopping Sight Distance

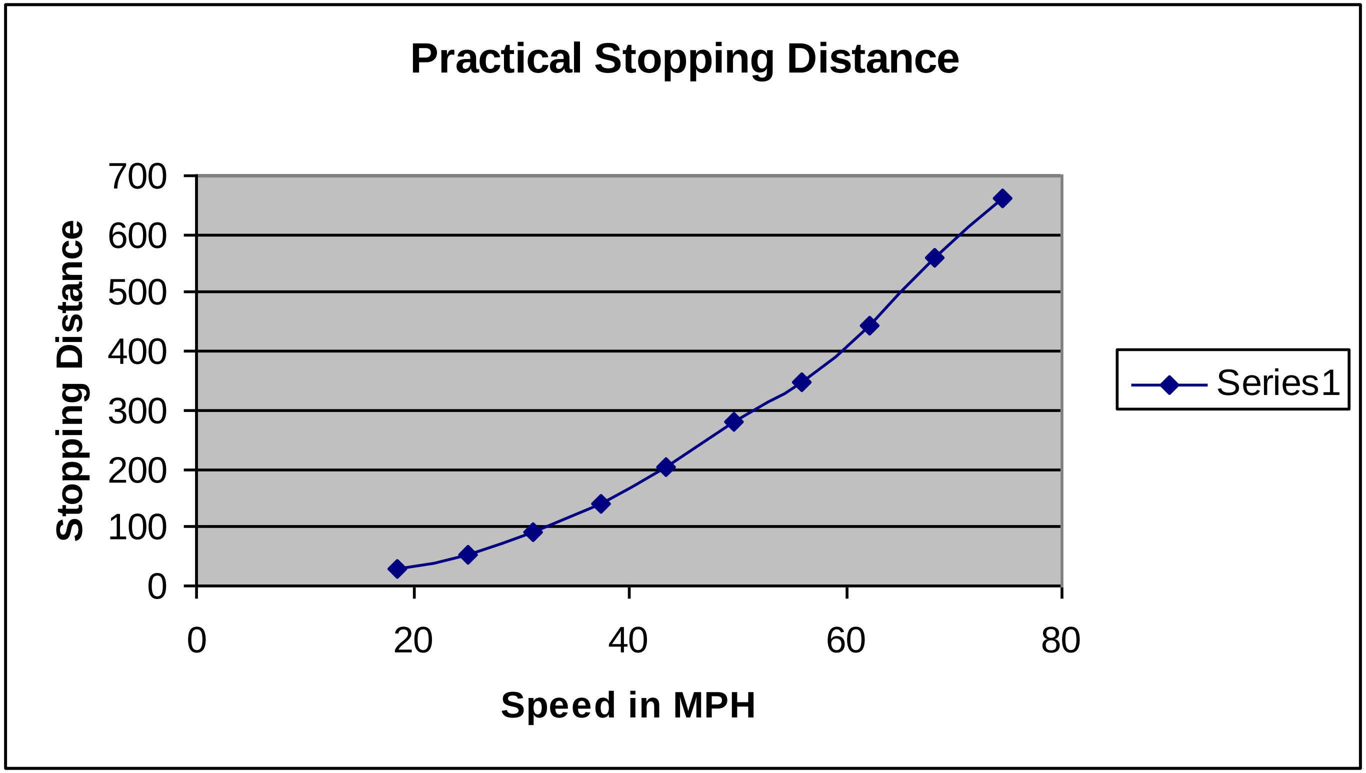


Distance to stop vehicle

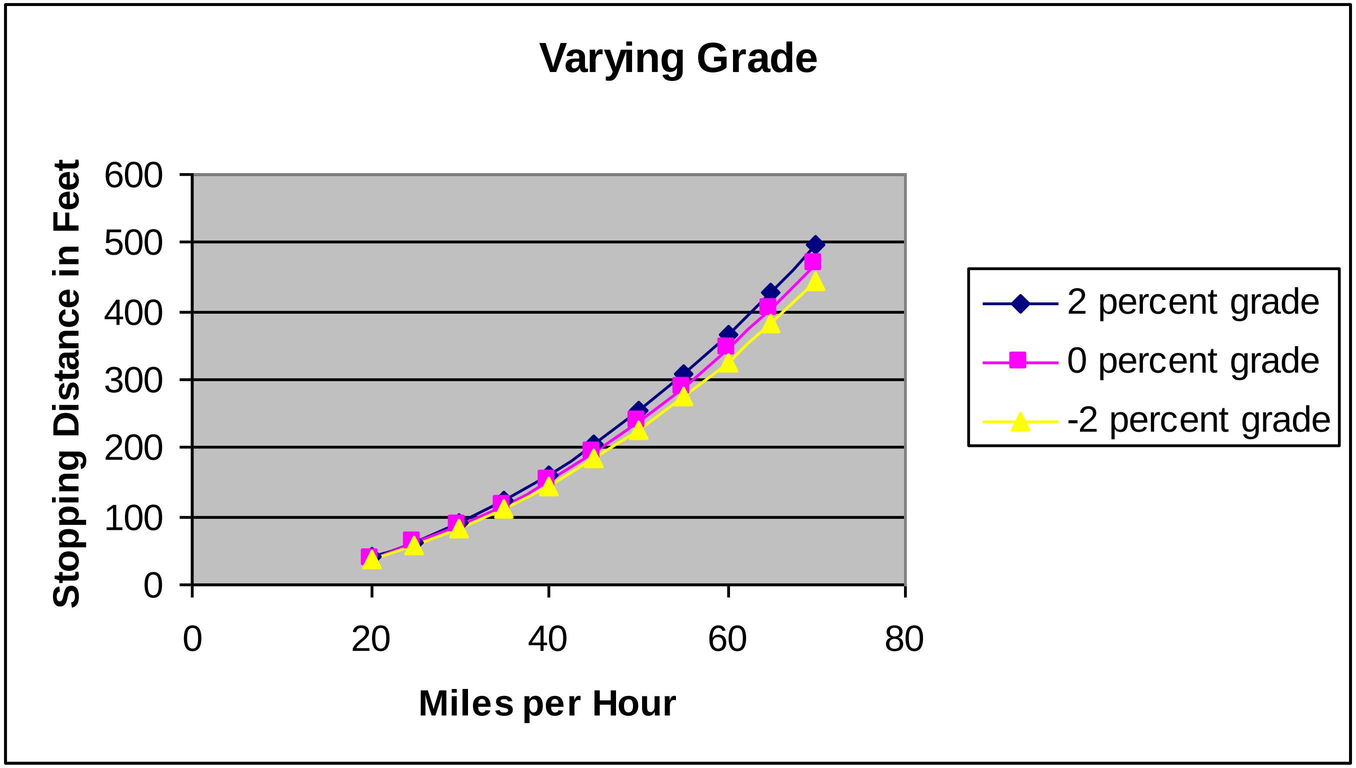
Coefficient of friction, f

Pavement condition	Maximum	Slide
Good, dry	1.00	0.80
Good, wet	0.90	0.60
Poor, dry	0.80	0.55
Poor, wet	0.60	0.30
Packed snow and Ice	0.25	0.10

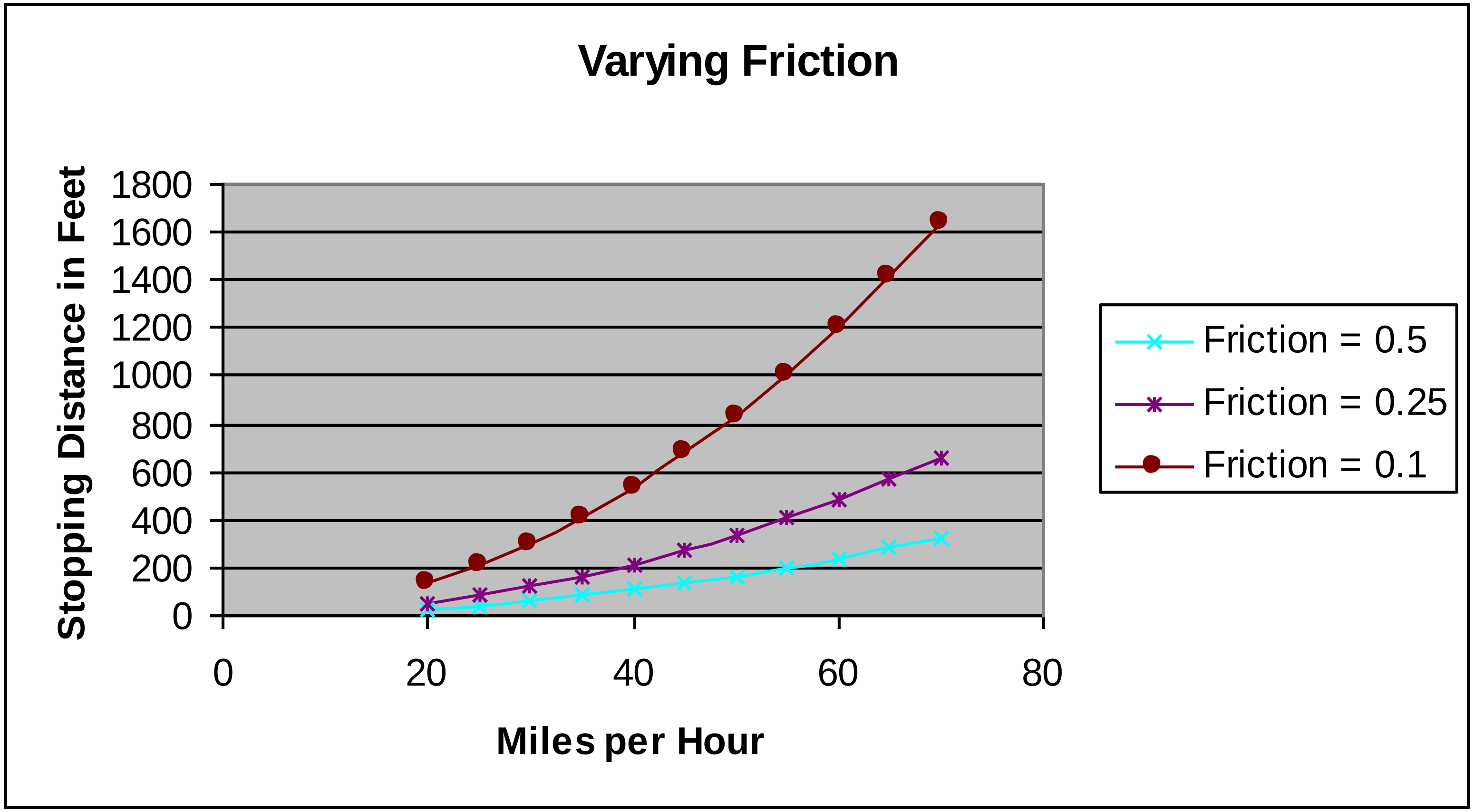
Stopping distance



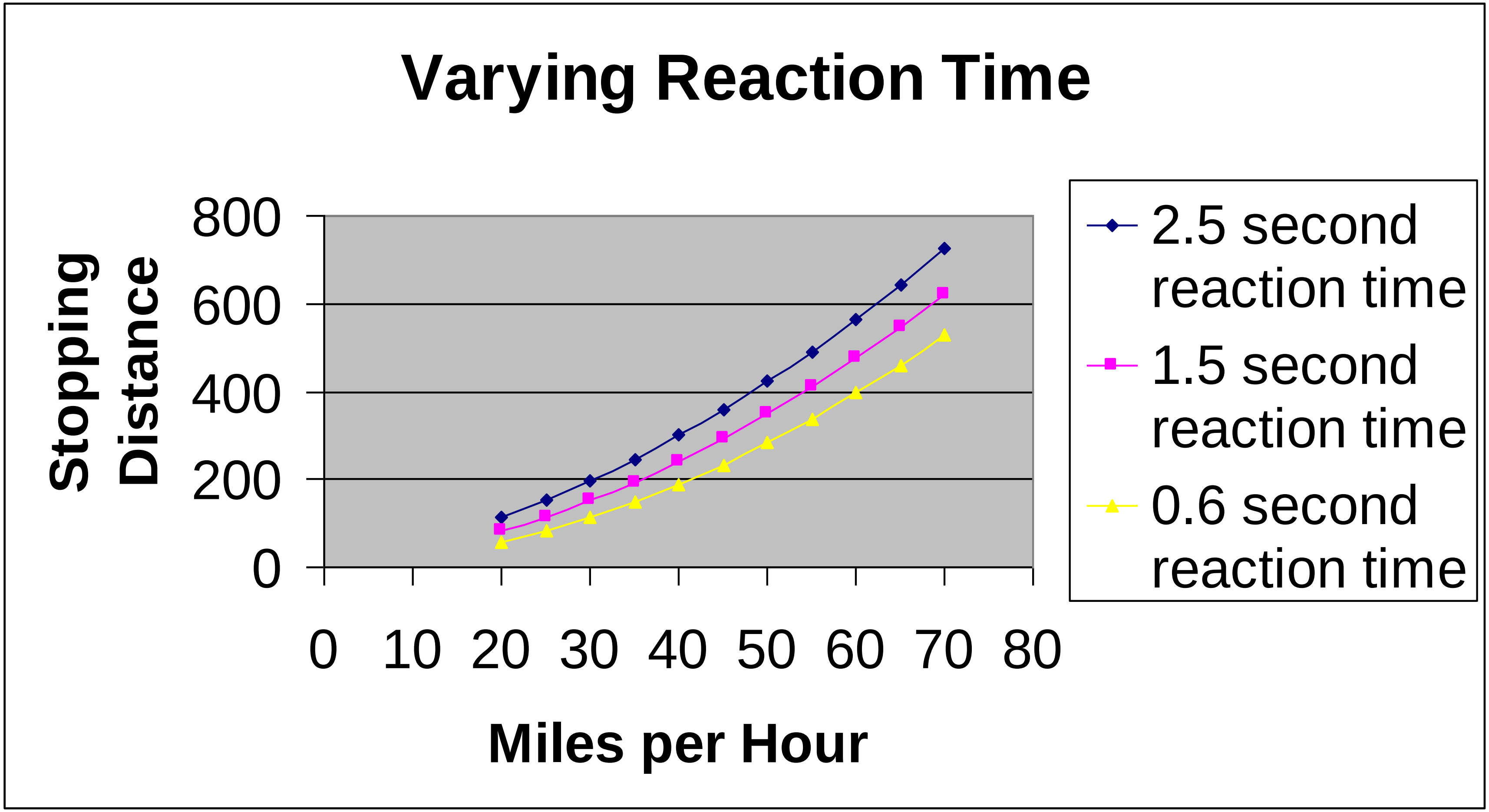
Grade impacts on stopping



Friction impact on stopping



Impact of reaction time



Important Sight Distances

1. Stopping
2. Decision
3. Passing
4. Intersection
5. Crossing RR

Sight Distance in Design

- For safety, should provide sight distance of sufficient length so that drivers can control the operation of their vehicles to avoid striking an unexpected object in the traveled way - STOPPING SIGHT DISTANCE (SSD)
- Certain 2-lane roads should have sufficient sight distance to enable drivers to occupy the opposing traffic lane for passing other vehicles without risk of crash - PASSING SIGHT DISTANCE (PSD)

Green Book (AASHTO) Policy Question

- Sight distance assumes drivers are traveling at:
  - A. The posted speed limit
  - B. 10 mph above the speed limit
  - C. The 85% percentile spot speed of the facility
  - D. The design speed of the facility

Stopping Sight Distance (SSD)

- Required for every point along alignment (horizontal and vertical) – Design for it, or sign for lower, safe speed
- Available SSD = f(roadway alignment, objects off the alignment, object on road height
- SSD = PRD + BD (with final velocity V_2 = 0)

Criteria for Sight Distance

- Driver eye height: for passenger vehicle’s = 3.5 ft above surface
- Height of object in roadway = 2 feet (SSD) – why?
- Height of opposing vehicle = 3.5 feet (PSD)

Criteria for Sight Distance

- Driver eye height: for passenger vehicle's = 3.5 ft above surface
- Height of object in roadway = 2 feet (SSD) – why?
- Height of opposing vehicle = 3.5 feet (PSD)

Stopping Sight Distance

Distance to stop vehicle, includes P/R and braking distance

$$S = 1.47ut + \frac{u^2}{30(\{a/g\} \pm G)}$$

where:

D_b = braking distance

u = initial velocity when brakes are applied

f = coefficient of friction

G = grade (decimal)

t = time to perceive/react

a = vehicle acceleration

g = acceleration due to gravity (32.2 ft/sec^2)

Stopping Sight Distance

With assumed acceleration, using friction

$$S = 1.47ut + \frac{u^2}{30(f \pm G)}$$

where:

D_b = braking distance

u = initial velocity when brakes are applied

f = coefficient of friction

G = grade (decimal)

t = time to perceive/react

SSD Example

- A vehicle is traveling at uniform velocity, at t_0 the driver realizes a vehicle is stopped in the road ahead and the driver brakes
- Grade = + 1%
- $t_{P/R}$ = 0.8 sec
- The stopped vehicle is just struck, assume $v_f = 0$
- The braking vehicle leaves skid marks that are 405 feet long
- Assume normal deceleration (11.2 ft/sec^2)
- Should the police office at the scene cite the driver for traveling over the 55 mph posted speed limit?

SSD Example

$$SSD = 1.47ut + \frac{u^2}{30(\{a/g\} \pm G)}$$

Stopping distance = 405 feet

$$405 \text{ feet} = 1.47u(0.8 \text{ sec}) + \frac{u^2}{30(\{11.2/32.2\} + 0.01)}$$

$$405 \text{ feet} = 1.17u + \frac{u^2}{30(0.358)}$$

$$405 \text{ feet} = 1.17u + \frac{u^2}{10.73}$$

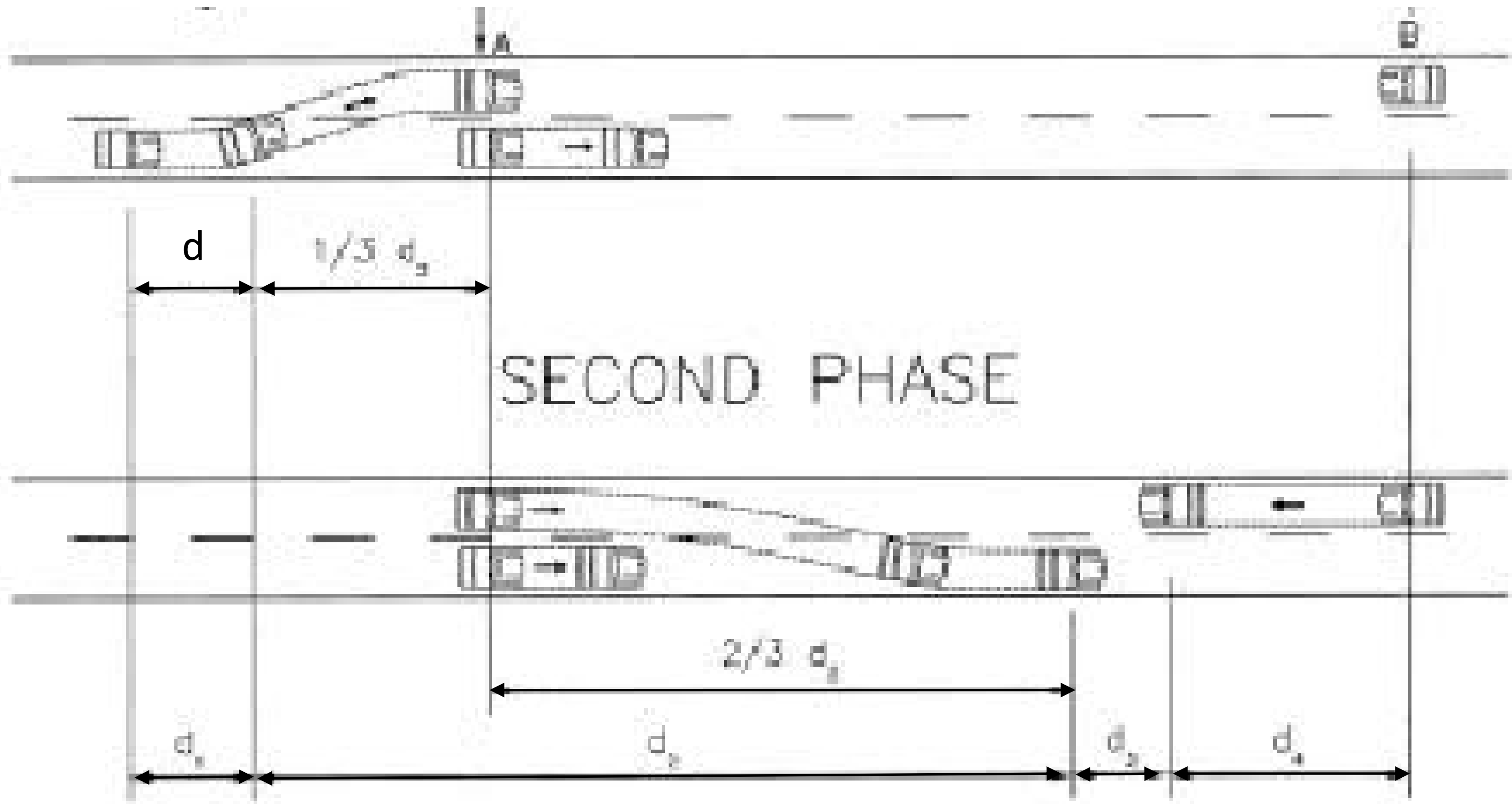
Solving for u, u = 59.9 mph

Passing Sight Distance

- Minimum distance required to safely complete passing maneuver on 2-lane two-way highway
- Allows time for driver to avoid collision with approaching vehicle and not cut off passed vehicle when upon return to lane
- Assumes:

1. *Vehicle that is passed travels at uniform speed*
2. *Speed of passing vehicle is reduced behind passed vehicle as it reaches passing section*
3. *Time elapses as driver reaches decision to pass*
4. *Passing vehicle accelerates during the passing maneuver and velocity of the passing vehicle is 10 mph (16kph) greater than that of the passed vehicle*
5. *Enough distance is allowed between passing and oncoming vehicle when the passing vehicle returns to its lane*

Passing Sight Distance



Passing Sight Distance

PSD = $d_1 + d_2 + d_3 + d_4$

d_1 = distance traveled during perception/reaction time and distance traveled while accelerating to passing speed and when vehicle just enters the left lane

$$d_1 = V_o t + \left(\frac{V_f^{\,2} - V_o^{\,2}}{2a}\right)$$

where

t = perception/reaction time (sec)

Vo= average speed of passing vehicle (m/s)

Vf= speed as vehicle enters the left lane (m/s)

a = acceleration (m/s^2)

Passing Sight Distance

PSD = $d_1 + d_2 + d_3 + d_4$

d_2 = distance traveled by vehicle while in left lane

Passing veh. driver must traverse the clearance distance between itself and the slow vehicle, the length of the slow vehicle, its own length, the length of the clearance distance between itself and the slow veh. at lane re-entry

$$d_2 = Vt$$

$$t = V / D,$$

$$where: D = (6 + 6.7 + 6.7 + 6)m, \ and$$

$$V = 16kph(relative speed of \ passing \ vehicle]$$

Passing Sight Distance

$PSD = d_1 + d_2 + d_3 + d_4$

d_3 = clearance distance between the passing vehicle and the opposing vehicle at the moment the passing vehicle returns to the right lane. Usually d_3 is taken equal to 75m.

d_4 = distance traveled by opposing vehicle during 2/3 of the time the passing vehicle is in the left lane. (d_4 usually taken as 2/3 d_2)

PSD

A vehicle moving at a speed of 80kph is slowing traffic on a two lane highway. What passing distance is necessary, in order for a passing manoeuvre to be carried out safely?

Use PRT=2.5sec, passing vehicles acc. rate= 0.67m/sec^2, Vo of passing =80kph, V of opposing vehicle =95kph, Lengths of all veh = 6.7m, clearance distances b/n passing and slow veh at lane change and at re-entry=6m, clearance distance b/n passing and opposing vehs at lane re-entry=75m.

Sight Distances

Design Speed (km/h)	Coefficient of Friction (*f*)	SSD (m)	PSD (m) from formulae	Reduced PSD for design (m)
20	.42	20	160	50
30	.40	30	217	75
40	.38	45	285	125
50	.35	55	345	175
60	.33	85	407	225
70	.31	110	482	275
85	.30	155	573	340
100	.29	205	670	375
120	.28	285	792	425

How are these factored into design

Design criteria must be based on the capabilities and limitations of **most** drivers and pedestrians.

References

- Wright (1996) Highway Engineering, J. Wiley