**ROADWAY DESIGN** – in a nutshell 😊

<table>
<thead>
<tr>
<th>CRITERIA:</th>
<th>TOPICS:</th>
<th>TOOLS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Safety*</td>
<td>• SDs</td>
<td>• Geometry</td>
</tr>
<tr>
<td>• Cost*</td>
<td>• HCs</td>
<td>• Physics &amp;</td>
</tr>
<tr>
<td>• Speed/Delay</td>
<td>• VCs</td>
<td>Calculus</td>
</tr>
<tr>
<td>• Comfort</td>
<td>• Cross-sections</td>
<td>• Experiments,</td>
</tr>
<tr>
<td>• Equity</td>
<td>• Intersections</td>
<td>Data &amp; Statistics</td>
</tr>
<tr>
<td>• Environment</td>
<td>• Operations</td>
<td>• Eng’g Economy</td>
</tr>
<tr>
<td>• Aesthetics …</td>
<td>• Other travelers</td>
<td>• Computers &amp;</td>
</tr>
<tr>
<td>* also Topics</td>
<td>• Drainage …</td>
<td>CAD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Hydraulics …</td>
</tr>
</tbody>
</table>

**ROADWAY DESIGN**: Overview of HC Eqns.

**DESIGN COMPUTATIONS: SDs + HORIZ CURVES**

\[
\begin{align*}
L_r + a_g + V_d + G & \rightarrow SSD \\
V_d & \rightarrow PSD \\
SD + R (\pm \Delta) & \rightarrow M_{\text{min}} \\
V_d & \rightarrow f_{\text{max}} + R \rightarrow e_d + W + N + A_{\text{edge}} \rightarrow L_r \\
\text{Sta}_{\text{PC}} + T & \& L \rightarrow \text{Sta}_{\text{PQ}} & \& \text{Sta}_{\text{PT}} \\
L_r + e_d + e_{\text{HC}} & \rightarrow L_r
\end{align*}
\]

\[
L_r = L_r + R \rightarrow \Delta_r + l \rightarrow \delta_1 + X_1 + Y_1 \quad \text{Spiral Transition}
\]

\[
R_{\text{inner (2)}} \rightarrow R_{\text{outer (1)} \& (3)} \rightarrow \Delta_{2} + p_{1 \& 3} \quad \text{CC Transition}
\]
**ROADWAY DESIGN**: Overview of VC Eqns.

**DESIGN COMPUTATIONS: SDs + VERT CURVES**

\[ t_i + a_n + V_d \rightarrow SSD \]

\[ V_d \rightarrow PSD \]

\[ G_1 & G_2 \rightarrow A \]

\[ SD + A + h_{eye} + h_{obj} \rightarrow L_{min,crest} \]

\[ SD + A + h_{famp} \rightarrow L_{min,sag} \]

\[ A + G_1 + Elev_{fpc} \rightarrow Elev(x) \]

---

**HORIZONTAL CURVES**

Lesson 6’s Objectives …

- Define horizontal curve terminology & dimension curve elements. (Review)
- Compute deflection angles & distances.
- Calculate HC sight distances.
- Any safety or other issues we need to think about when designing HCs?

---

Plans for FM439 Alignment (Courtesy of Waco District’s Road Dept. 4/16/01)
HORIZONTAL ALIGNMENTS…

• Typically, a series of simple/circular curves joined by straight tangents.
• Compound & spiral curves also may be used.

Questions:
? : What kind of curve takes one from a straight \([R=\infty]\) segment to a circular curve \([R=\text{constant}]\)?
? : Why might one want to include spiral curves?

Some Geometric Relations: A Review

For a right triangle with hypotenuse "H":
\[ L_{\text{hyp}} = H \cdot \cos(\alpha) \text{ & } L_{\text{side}} = H \cdot \sin(\alpha), \]
For all triangles:
\[ \frac{\sin(\alpha_1)}{L_1} = \frac{\sin(\alpha_2)}{L_2} = \frac{\sin(\alpha_3)}{L_3} \]
\[ L_3 = \sqrt{L_1^2 + L_2^2 - 2L_1L_2 \cos(\alpha)} \]
\[ \sec(\alpha) = \frac{1}{\cos(\alpha)} \text{ & } \csc(\alpha) = \frac{1}{\sin(\alpha)} \text{ & } \cot(\alpha) = \frac{1}{\tan(\alpha)} \]

Alignment Terminology: A Review

• Station = ???

Questions to solve in pairs:
• PI = ???
• I or \(\Delta\) = ???
• PC = ???
• PT = ???
• \(T\) = ???
• \(L\) = ???
• Given a simple curve’s radius \(R\) & \(\Delta\), how can one compute \(T\) & \(L\)? (See next slide for diagram…)

(c) Kockelman
More HC Terms & Calculations:

Given $R$ & $\Delta$, compute the following…

• $LC = \text{Length of Long Chord} = ???$
• $E = \text{External Distance} = ???$
• $M = \text{Middle ordinate distance} = ???$
• $D_a$ & $D_c = \text{Degree of curve -- using Arc & Chord definitions} = \text{angle [in degrees] subtended by an arc or chord of length 100 feet [or meters]}
• $R = ?/D_a$
• $\delta_i = \text{Deflection Angle from tangent to stake point } i$
• $c_i = \text{Chord Length to stake point } i$

Questions:

• The angle between a tangent & a chord is what fraction of the interior angle subtended by that chord?
• Where does one first place the theodolite when surveying (& staking) a HC?
LOCATING HCs: Surveys & Staking

• Surveyors begin from the PC, sight on the PI, & stake points from this position (when feasible).

• A series of deflection angles ($\delta$ – from the back tangent) & chord lengths ($c$ – from the PC) define key HC points, every one or two full stations (i.e., every even ~100 to 200 feet).

• To reach these full stations, first & last $\delta$'s & $c$'s are “odd” values.

Example Survey Series (every 200 ft):

<table>
<thead>
<tr>
<th>Point</th>
<th>Station</th>
<th>Defl. Ang.</th>
<th>Chord</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station (deg)</td>
<td>Length</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>30+52.125</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>32+00</td>
<td>4.236</td>
<td>147.740</td>
<td></td>
</tr>
<tr>
<td>34+00</td>
<td>9.968</td>
<td>346.124</td>
<td></td>
</tr>
<tr>
<td>36+00</td>
<td>15.695</td>
<td>541.046</td>
<td></td>
</tr>
<tr>
<td>38+00</td>
<td>21.425</td>
<td>730.567</td>
<td></td>
</tr>
<tr>
<td>40+00</td>
<td>27.155</td>
<td>912.787</td>
<td></td>
</tr>
<tr>
<td>42+00</td>
<td>32.884</td>
<td>1085.886</td>
<td></td>
</tr>
<tr>
<td>44+00</td>
<td>38.614</td>
<td>1248.135</td>
<td></td>
</tr>
<tr>
<td>46+00</td>
<td>44.343</td>
<td>1397.913</td>
<td></td>
</tr>
<tr>
<td>PT</td>
<td>46+22.921</td>
<td>45.000</td>
<td>1414.214</td>
</tr>
</tbody>
</table>

HC SIGHT DISTANCE:

• $v_j$ & $a_b$ → $d_v$, $d_p$, & $d_d$

• Check roadside clearance from inside lane centerline ($M$) to ensure sufficient sight distances.

Exh. 3-54
AASHTO 2004, p.227
Exh. 3-53 (p. 226):

Plot of $R$ vs. $M$ – for various $V_d$ (& SSD)

• What assumptions does this figure make?
• Students should be able to derive the equation…

$$M = R \left( 1 - \cos \frac{28.65S}{R} \right)$$

HC Sightline Questions:

• Using Exh. 3-53, what is the closest one would want to plant trees along an $R = 1,095$ ft curve with a design speed of 60 mph?

• How much sight distance does one need for safe stopping & for safe passing at this speed?

• Does it make sense to allow passing on this curve?

Cutback Needs when $S > L$

Example: $v_d = 60$ mph → $S = $ PSD = 2135 ft, $R = 1095$ ft & $\Delta = 60^\circ$ → $L = 1146$ ft
Sight distance limitations on HCs…

In Summary: What have we learned?

• How to compute \( T, E, M, LC \), chord lengths \( (c) \), & deflection angles \( (\delta) \).

• How to compute sight distance or minimum cut-backs on HCs.

BANKING & ITS DEVELOPMENT

Lesson 7’s Objectives …

• Compute safe speeds & superelevation for avoiding both slip & roll.
• Calculate runoff & runout lengths, as a function of speeds, lane widths, & banking.
• Develop (& undevelop) superelevation on horizontal curves.
• Compute station locations for critical development points.
VEHICLE FORCES

?: What Forces typically act on vehicles?

VEHICLE SLIP & ROLLOVER

?: What two negative events can occur when going too fast on a curve?

?: What three variables determine centrifugal force on a vehicle? What is the equation for $F_c$?

?: What do we do to counteract vehicle overturn & slip problems?

Superelevation/Banking

<table>
<thead>
<tr>
<th>Superelev. Deficiency</th>
<th>AMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>1.06</td>
</tr>
<tr>
<td>0.03</td>
<td>1.09</td>
</tr>
<tr>
<td>0.03</td>
<td>1.12</td>
</tr>
<tr>
<td>0.03</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Centrifugal Force FBD:

\[ e = \text{rate of superelevation} \]
\[ f_s = \text{coefficient of side friction} \]

Superelevation:

“\( e \)” = cross-slope = degree of banking

\[ e = \text{superelevation rate} = \text{rise/run} = \tan(\alpha) \]

?: What considerations would limit \( e \) to a maximum value?

- Regions/States often specify an \( e_{\text{max}} \):
  - \( e_{\text{max}} \leq 8\% \) in colder, icy climates & urban conditions
  - \( e_{\text{max}} \approx 10\% \) in warmer climates (but also WashDOT!)
- \( NC = \text{Normal cross-slope/crown} \approx -1\% \text{ to } -4\% \)

?: Where is \( NC \) used? And why do we use it?

Side Friction: Q&A

- Upon \textit{skidding}, \( f_{s,\text{actual}} \approx 0.35 \) on bald tires & wet surface at 45 mph.
- Does \( f_s \) fall or rise with increases in speed?
- AASHTO’s \textbf{Exh. 3-15} recommends maximum \( f_{s,\text{design}} \approx 0.08-0.18 \).
- Is \( f_s \) less than or greater than braking friction, \( f \)?
- If \( a_b = -11.2 \text{ ft/s}^2 \), what is braking friction \( f \)?
Questions:

1. Solve for the relationship which allows a vehicle to not slip while rounding a curve (i.e., outward acceleration = zero).

2. If a fast-moving vehicle were to roll over on a curve, where is the point over which the car would roll?

3. Solve for the moment relationship which holds when a vehicle is in this critical condition.

Centrifugal Force FBD:

\[ y = \text{Vert. distance to COG} \]
\[ x = \text{Horiz. distance, from outside tire point} \]
\[ \sum F_i = mg\cos(\alpha) + \frac{mv^2}{R} \sin(\alpha) = mg\sin(\alpha) - \frac{mv^2}{R} \cos(\alpha) \]
\[ \sum M_i = \sum F_i d_i = mg\sin(\alpha) y + mg\cos(\alpha) x + \frac{mv^2}{R} \sin(\alpha) x - \frac{mv^2}{R} \cos(\alpha) y \]

Slipping Solution

\[ \frac{v^2}{gR} = \frac{e + f_s}{1 - ef_s}, \text{ in CONSISTENT units,} \]

\[ \rightarrow \frac{v^2}{15R} = \frac{e + f_s}{1 - ef_s} \approx e + f_s \text{ (conservatively),} \]

where \( V = \text{mph,} \ R = \text{ft,} \) and \( e \ & f_s = \text{dimensionless.} \)
**Rolling/Overturning Solution**

\[
\frac{v^2}{gR} = \frac{x + ye}{y - xe}, \text{ in CONSISTENT units,}
\]

\[
\rightarrow \frac{V^2}{15R} = \frac{x + ye}{y - xe}
\]

where \(V = \text{mph}, R = \text{ft}, \)

\(x\) & \(y\) = horiz. & vertical distances to COG

(in any units), and

\(e = \text{dimensionless}.\)

---

**Risk of Rollover:** How high is your vehicle? 😊

---

**Example Problem:**

What’s the **maximum safe speed** a vehicle can travel around a \(R = 650\) ft curve assuming a coef. of side friction \(f_s = 0.2\) if the curve’s banked at \(e = 5\%\) & the vehicle’s center of gravity (COG) is \(y = 5\) ft above ground & its track width (distance between left & right tires) is \(8\) ft \((= 2r_{COG})\)?
REVIEW: Key Curve Equations

\[ V_{\text{max,slipping}} = \sqrt{\frac{Rg(f_e + e)}{1 - f_e e}} \approx \sqrt{Rg(f_s + e)} \]

\[ V_{\text{max,overturning}} = \sqrt{\frac{ye + x}{y - xe}} \]

Tough Question:

We can rely on both \( e \) & \( f_s \) to protect drivers on curves: \( \frac{v^2}{gR} \approx e + f_s \)

- If a design does not “max” out on both \( e \) & \( f_s \), how much should one depend on \( e \) versus \( f_s \)?

Methods for Distributing \( e + f \)  
Exh. 3-13, AASHTO 2004, p.141

Note: Green Book uses 5 (due to speeders); consistency may suggest 1 is best.
Exh. 3-22: $e_{\text{design}}$ for $e_{\text{max}} = 10\%$, given $R$

In Summary: What have we learned?

- What 3 conditions must be checked on HCs?
- How do we compute min. $R$ or max. $V$ on HCs?
- What can we do if a HC is unsafe?
- How should we balance friction & banking?

Beyond the State of Practice…

Always Slip First?

HC Speeds at impending Skid or Rollover

Source(s): ITE (1992), Adapted from FHWA (1990)
Lesson 7b’s Objectives

- Calculate runoff & runout lengths, as a function of speeds, lane widths, & banking.
- Develop (& undevelop) superelevation on horizontal curves.
- Compute station locations for critical development points.

Developing Superelevation: Simple HC
Aerial & Cross-Sectional Views

DEVELOPMENT OF SUPERELEVATION

- Developing $e$ means warping/rotating a pavement from a typical crown (~2%) to design banking ($e_{\text{design}}$).

- This requires that one RUNOUT the adverse crown slope on the outside edge of pavement (this is done wholly on the Tangent)
  - AND then RUNOFF / DEVELOP the Full $e$ (to get from 0% up to $e_{\text{design}}$).
HC Alignment:

- Plan
- Cross-Section
- Edge Views

**ANIMATION!!!**

- Development length = Runoff length = $L_r$ = Length over which outside lanes of no cross-slope are raised to lie in a plane with inside lanes AND then the entire plane is rotated to design superelevation ($e_{\text{design}}$).

- Runout lengths ($L_t$) are computed using the same relative edge slope as runoff lengths (e.g., 1:200 at 50 mph, 1 lane; see Exh. 3-30).

> What is the equation relating $L_r$, $L_t$, $e_{\text{crown}}$ & $e_{\text{design}}$?

- For circular curves, AASHTO recommends that 60-80% of runoff occur on the tangent $\rightarrow$ Often use $\sim 2/3$ in practice.

- With “transition curves”, runoff is done where?

- AASHTO’s Exh. 3-25 to 3-29 & 3-32 prescribe different $R$ & $L_r$, for various $e_{\text{design}}$, over different $v_d$, assuming different $e_{\text{max}}$ (ranging from 4% to 12%)...
Exh. 3-27: $c_{\text{design}}$ & $R_{\text{min}}$ for HCs

AASHTO 2004, p. 170

Exh. 3-32: $L_r$ for HCs (2 & 4 lanes)

AASHTO 2004, p. 181

Example Problem (to solve in teams):

• If we have a 2-lane road in Texas with $NC = 2\%$, $v_d = 60$ mph & we choose to use $R = 1500$ ft., what runoff & runout lengths should we use?

• And where should these occur, if our PC’s station is 21+50.00 & our PT’s station is 45+00.00?
Developing & Undeveloping Superelevation on a pair of Reverse HCs (with spirals in between)

Development Lengths for Wider Pavements:

? : Why do we use longer $L_r$ for wider pavements?

- $L_{r,4\text{-lane}} \sim 1.5 \ L_{r,2\text{-lane}}$ & $L_{r,6\text{-lane}} \sim 2 \ L_{r,2\text{-lane}}$
  
  (See adjustment factors, $b_w$, in Exh. 3-31.)

$\Delta = \Delta_{\text{adj}} = \frac{W e_p b_w}{\Delta_{\text{adj}}}$

? : If a two-lane road of 50 mph with 10 ft. lane widths is to be superelevated to 10%, what should $L_r$ be?

Development Lengths for Wider Pavements: An Example
In Summary: What have we learned?

• How are runoff & runout related?

• What charts & tables are useful to us for computing runoff for different speeds, lane widths, & superelevation?

• How can we illustrate edge placement, relative to centerlines, on warped pavements?

TRANSITION CURVES

Lesson 8’s Objectives …

• Identify design situations for use of compound & spiral curves.

• Specify & locate these curves – graphically & mathematically.

• Calculate key angles & distances characterizing these transition curves.

Spirals & CCs are Transition Curves…

• Transition from a tangent to a tight turn (& back!).

• Spirals most common along highways.

• Compound curves most typical for turning at intersections (to accommodate off-tracking).

• Also use between two very distinct circular curves (e.g., \( R_1 > 2R_2 \)).

• Note: Tapers = straight segments that also may be used, from curve to tangent.
Questions: (1) What's $p$?  
(2) Where can we show $\Delta_s$?

**SPIRAL CURVES: Key Points**

- What are their main benefits?
- Most helpful on tight curves (Exh. 3-36: $R_{\text{max}}$ for spiral use).
- We develop the banking on spirals (determine $L_s$ & let $L_r = L_s$).

**Specifying $L_s$:** Balancing comfort & length

- $L_{s,\text{natural}}$ [ft] = $2.9V = 2$ sec dist. $\rightarrow$ Possibility for high edge gradients

$$L_{s,\text{edge gradient}} \text{ (Exh. 3-35 through 3-39): } L_s = \frac{(\text{min})R_s}{\Delta_{\text{edge}}}$$

$$L_{s,\text{min}} = \max\left(\frac{24p_{\text{min}}R_s}{3.15V^1}, \frac{3.15V^1}{RC}\right)$$

$$L_{s,\text{max}} \approx \frac{24p_{\text{max}}R}{C = \text{max. lateral jerk (4 ft/s}^3\text{)}}$$

$p_{\text{max}}$ & $p_{\text{min}} = 3.3$ & 0.66 ft
Euler’s spiral (a.k.a. the “clothoid”):

- This is a popular and specific spiral curve…
- Its radius varies inversely with the distance measured/traveled along the spiral.
- \( R_l l = R L_s \) where \( l \) = distance from the tangent (TS point) & \( R \) = final, minimum radius

Geometry of Spiral Curves:

\( PI \) = Point of Intersection of Forward & Back Tangents
\( TS \) = Point from Tangent to Spiral (or PS)
\( SC \) = Spiral to Curve Point
\( CS \) = Curve to Spiral Point
\( ST \) = Spiral to Tangent Point (or PT)
\( L_s \) = Length of spiral section
\( \Delta \) or \( \Delta \) = Angle of change in bearing/direction of tangents
\( \Delta \) = Angle subtended by full Circ. arc w/out Spirals

Geometry of Spiral Curves (continued)

\( \Delta_s = \) Subtended angle & change in bearing of spiral’s tangents = \( 90 \ L_s / \pi R \) (degrees) = \( L_s / 2R \) (radians)
\( \Delta_s = \Delta - 2\Delta_s = \) Angle subtended by interior, Circular curve
\( \delta = \) Deflection angle from TS to SC = \( \Delta_s / 3 \)
\( \delta = \) Staked deflection angle from TS to point at distance \( l \)
\( \Delta_s = \) Subtended angle from TS to point at distance \( l \)

\[ \Delta_s = \frac{\Delta_s}{L_s} \quad \delta_s = \frac{\Delta_s}{3} = \frac{\Delta_s L_s^2}{3L_s} \approx \frac{30L_s^3}{\pi RL_s} \]
**Laws of Euler’s Spiral:**

- \( R_j = \text{Constant} = R_{\text{min}} L_j \)
- Spiral subtended angles (\( \Delta \)) are proportional to the squares of the spiral lengths from the TS.
- Spiral deflection angles (\( \delta \)) are almost proportional to the squares of the spiral lengths from the TS.
- Tangent offsets (\( y \)) are almost proportional to the cubes of the spiral lengths from the TS.
- The spiral bisects the throw, & the throw bisects the spiral!

![Diagram of Euler's Spiral](image)

**Staking a Spiral Curve: x & y**

Note:
- \( \theta_i \) [rads] = \( \Delta_i \) [degs]
- \( \phi_i \) [rads] = \( \delta_i \) [degs]

**Equations: For Staking Points Along a Spiral**

\[
\begin{align*}
X_{\text{spiral}} &= L \left[ 1 - \frac{\theta_i^2}{10} + \frac{\theta_i^4}{216} - \frac{\theta_i^6}{9360} + \cdots \right] \\
Y_{\text{spiral}} &= L \left[ \frac{\theta_i}{3} - \frac{\theta_i^3}{42} + \frac{\theta_i^5}{1320} - \frac{\theta_i^7}{75600} + \cdots \right]
\end{align*}
\]

where \( x_i \) = distance along tangent to stake point,
\( y_i \) = distance perpendicular to tangent, out to stake point.
\( L \) = distance along spiral, to stake point, &
\( \theta_i \) = [RADIANS of interior angle] = \( \frac{L - \delta}{2 R} \) [rads] = \( \frac{\Delta_i \pi}{180} \) = \( \frac{2 \pi \delta_i}{360} \)

where \( \delta_i \) = [DEGREES] = deflection angle from TS out to stake point.

Note: \( p = \text{"throw"} = \text{lateral shift of circular arc from tangent} \)
Example Spiral Computations:

Design the tightest safe 4-lane HC with spiral that you can. Assume \( \Delta = 90^\circ \), \( V_d = 60 \text{ mph} \) & \( e_{\text{max}} = 10\% \).

1. \( V \) \& \( e_{\text{max}} \rightarrow R_{\text{min}} = 1095 \text{ ft} \) (Exh. 3-28)
2. \( L_{\text{ext}} = 2.9V = 174 \text{ ft} \)
   vs. Exh. 3-32 (edge gradient method) suggests \(-400 \text{ ft} \)
3. \( L_{\text{local}} = 2.9 \frac{V^2}{R_{\text{max}}} = 294 \text{ ft} \) → Let \( L_s = 300 \text{ ft} \)
4. \( \Delta_s = 90 - \frac{L_s}{R} = 7.849^\circ \) & \( \Delta_s = 90 - 2 \times 7.849 = 74.302^\circ \)
5. \( \theta_s = 2 \pi \Delta_s / 360 = L_s^2 / (2RL_s) = 300 / (2 \times 1095) = 0.1370 \text{ rads} \)
6. \( X_s = 300(1 - 0.1370^2/10 + 0.1370^4/216 - \ldots) = 299.437 \text{ ft} \)
   \& \( Y_s = 300(0.1370/3 - 0.1370^3/42 + 0.1370^5/1320 - \ldots) = 13.680 \text{ ft} \)

**Question:** How can we compute the offset, \( p \)?

**COMPOUND CIRCULAR CURVES:**

**Key Points**

?: When do we most often use *compound curves*?

**Types of Compound Curves:**

- Three-Centered vs. Two-Centered
- Symmetric vs. Asymmetric

**Points & Variables of Interest:**

- PI, PC, & PT, plus PCC_i’s
- \( \Delta_i \)’s, \( R_i \)’s, & \( p_i \)’s (a.k.a. “offsets”)
Compound Curves & Approximations:

Design Choices Along Highways ($\Delta$ & $R_2$ = known):
• Let $R_1 = R_3 \approx 1.5-2.0 \ R_2$
• Let $L_1 = L_3 = L_r$
  $\rightarrow \Delta_1 = \Delta_3 = ???$ & $\Delta_2 = ???$

Designing Corners for Vehicle Paths ($\Delta$ = known):
• Exh. 9-19: Circular Curve with Tapers
• Exh. 9-20: Symm. & Asymm. 3CCC, 8 vehicle types
• Exh. 9-42: Symm. 3CCC, with Islands, 3 veh. types
• Exh. 9-43: Off-ramp Compound Curve Specs.

Compound Curves with AASHTO Guidelines:

Examples

Task: Design a Corner Edge for WB50's with $\Delta = 90^\circ$.

3CCC:
• Without Islands (Exh. 9-20)
  Symmetric: $R'$s = 180'-60'-180', $p'$s = 6.5 ft
  Asymmetric: $R'$s = 120'-40'-200', $p'$s = 2.0 & 10 ft
• With Islands (Exh. 9-42)
  $R$'s = 180'-65'-180', $p$ = 6.0 ft, $LW$ = 20 ft

Circular Curve with Tapers:
• Without Islands (Exh. 9-19)
  $R = 60'$, $p = 4.0'$, Taper rate = 1:15

Example Images of Actual Applications
Curve with Tapers

* Note that the offset is to the curve, not to the taper. *

Ch. 9’s Curb Design: Effect of Radii on Right Turn Paths (Exh. 9-29, AASHTO 2004, p. 616)

Curb Design:
Curves + Tapers vs. 3CCC
for SU Trucks & City Transit Buses

(Exh. 9-19 to 9-28 for radii, taper rates, & offsets. AASHTO 2004, p. 584+)
3CCC Computations: Example

? : Design the tightest safe 4-lane 3CCC you can, with $\Delta = 90^\circ$, $V = 60$ mph & $e_{\text{max}} = 10\%$

1. $R_{\text{min}} = 1095$ ft (Exh. 3-28 or $v^2/g(e+f) = 882/[32.2(0.10+0.12)]$

2. Let $R_1 = R_3 = 1.75 \times R_2 = 1916$ ft $\approx 1920$ ft

3. $L_1 = L_2 = 400$ ft (Exh. 3-32 or via computations of edge gradient: $L_{\text{edge}} = 1.5 L_{\text{edge},2\text{-lane}} = 1.5 \times 222$, where $1.222 = \text{edge gradient}$ for 60 mph on 2-lane road [Exh. 3-30])

3. $\Delta_1 = \Delta_2 = 360 L_2/2 R_1 = 11.937^\circ$ & $\Delta_1 - 90 - 2 \times 11.937 = 66.127^\circ$

4. $p_1 = p_2 = (R_1 - R_2)(1 - \cos(\Delta_1)) = 17.84$ ft

Final Design Project Cells: Symmetric 5CCC
In Summary: What have we learned?

- Where do we include spirals in our designs?
- What are some key spiral relations?
- What charts & tables are useful to us for specifying compound curves at intersections?
- How can we diagram transition curves?

VERTICAL CURVES

Lesson 9’s Objectives ...

- Define terminology associated with vertical curves.
- Compute VC elevations, as a function of stationing (horiz. distance).
- Compute safe VC lengths & sight distances.
VERTICAL ALIGNMENTS

- Roadway Profiles = Tangent Gradelines + PARABOLIC curves
- Maximum desirable grades, $G$:
  $\approx 3\text{-}5\%$ (freeways) & $7\text{-}12\%$ (local streets)
- $G_1$ = In-coming grade (in direction of stationing) & $G_2$ = Out-going grade
- $A = G_2 - G_1$

? If $A < 0$, the VC is a crest or sag curve?

THE VC EQUATION:

- Recall: Distances = measured horizontally (x-axis in a profile view)
- $L_{vc}$ = horizontal distance from VPC to VPT
- Let $x$ = Distance from VPC to point on VC
- $y_{of}(x)$ = Offset = Vertical distance from incoming gradeline to point on parabola (*not an elevation*)

\[
\text{Offset from grade to VC} = y_{of}(x) = \frac{Ax^2}{200L}.
\]

Thus, Elev(x) = Elev$_{vc}$ + $\frac{G_2 x}{100}$ + $y_{of}(x)$;

Note: $A$ & $G = [%]$

(c) Kockelman
Some Other Considerations:

- What is the (horiz.) distance from VPC to VPI?
- \( E \) = External distance, from VPI to curve = \( y(L/2) \)
- \( K = L/|A| \) = measure of VC’s (inverse) curvature
- If \( K > 167 \) ft./% what kind of issues must be considered on curved roads?

Questions (to solve in pairs):

1. What could be a critical point on a VC – & why?
2. What is the location (\( x^* \)) of such a point?
3. What’s the horiz. length of gradeline between a crest & a sag curve with VPI’s at 25+00 & 35+00, \( G_1 = +1\% \), \( G_2 = -2\% \), \( G_3 = +1.5\% \), & curvatures (\( K \)) of 130 ft./%?
4. What are the elevations of critical points on this profile of 2 VCs? (to solve at home)
   
   (Hint: \( El(x^*) = El(VPC)+0.65 \) ft)

Important Design Heights (for VCs)

Based on studies of passenger cars & their drivers, AASHTO (2001) recommends/assumes:

- Driver’s eye height = 3.5’
- Object/obstruction design height = 2’
- Oncoming vehicle design height = 3.5’
- Headlamp height is assumed to be 2’ (\& 1° upward divergence).

Question: Under what specific conditions (i.e., sag/crest, day/night, stop/pass, ...) are each of these heights relevant?
Example Set-Up: Crest Curve $S > L$

Minimum CREST Curve Length Equations:

\[
L_{\text{min,crest}} = \begin{cases} 
\frac{AS^2}{200\left(H_{\text{obj}} + \frac{A}{H_{\text{obj}}}ight)} = \frac{AS^2}{2158} & \text{when } S < L \\
2S - \frac{200\left(H_{\text{obj}} + \frac{A}{H_{\text{obj}}}ight)^2}{A} = 2S - \frac{2158}{A} & \text{when } S > L 
\end{cases}
\]

where $S =$ sight distance needed [ft],

$A = ??$,

$H_{\text{obj}} = 3.5 \text{ ft} \& H_{\text{obj}} = 2.0 \text{ ft}$ [AASHTO standards, stopping].

?: When passing is the concern, $H_{\text{obj}} =$ ???

Minimum $L_{VC, Crest}$ for SSD Provision: Exh. 3-71, AASHTO 2004, p.271

(c) Kockelman
Example Problems:

1. If eye & object heights on a crest curve are standard, $v_d = 60$ mph, $G_1 = 6\%$ & $G_2 = -4\%$, what is the minimum safe $L_{VC}$?

2. Under the 1994 AASHTO standards, the object height was 6 in. What then was the minimum $L_{VC}$ recommendation?

Minimum SAG Curve Length Equations:

$$L_{\text{sag}} = \begin{cases} \frac{AS^2}{200(H_{\text{lamp}} + S \tan(\beta))} = \frac{AS^2}{400 + 3.5S} \text{ when } S < L, \\ \frac{2S - 200(H_{\text{lamp}} + S \tan(\beta))}{A} = 2S \cdot \frac{(400 + 3.5S)}{A} \text{ when } S > L \end{cases}$$

where \(H_{\text{lamp}} = 2.0 \text{ ft} \) & $\beta = 1^\circ$ [AASHTO standards]
Misleading the Motorist…

- Sag VC at Night
- Sag VC with Overpass

Underpasses:
- On sag curves, one must consider vertical clearance “C” to overhead obstruction (the underpass):

  Underpass Sag VC’s:

  \[
  L_{VC, sag} = \frac{[G_i - G_j]s^2}{800 \left( C - \frac{b_i + b_j}{2} \right)}, \quad \text{when } S \leq L
  \]

  \[
  L_{VC, sag} = \frac{2.5 \left( C - \frac{b_i + b_j}{2} \right)}{|G_i - G_j|}, \quad \text{when } S \geq L
  \]

  Note: High h's = critical
  → use \( b_i \) = truck – driver’s eye = 8 ft & \( b_j \) = rear lights = 2.0 ft.

  ★ Extra Credit for proving this!
Safety + Drainage + Comfort:

**Safety:** Sight distance = \( S \geq d_s \), & if feasible, \( \geq d_p \) (on 2-lane roads)

**Drainage:** On curbed roads, extra inlets, wide shoulders, &/or higher grades should be used if \( K = L_{VC}/A > 167 \) ft/%

**Comfort:** Need \( L_{VC} \) sufficiently long so \( a_{crest} < -3 \) ft/s² on crest curves & \( -1 \) ft/s² on sag curves

\[ \rightarrow L_{min/VC\_comfor} = \frac{AV_{s}^2}{140} \text{ (crest)} \, \frac{AV_{d}^2}{46.5} \text{ (sag)} \]

Example: 60 mph, \( A = -10\% \) (crest) \( \rightarrow L_{min/crest} = 257 \text{ ft} \ll 1500 \text{ ft safe} \)

In Summary: What have we learned?

• What is the *equation* for VC point elevations?

• What considerations determine *minimum VC lengths*?

• What *charts & equations* are useful to us for specifying safe VC lengths?

SPECIAL LANES

Lesson 10’s Objectives …

• Identify *special lanes* for extreme grade situations & describe their use …

  What are *examples* of these?
More VC Design Issues:

- **Speed Variations**: Higher accident rates.
- **HDV Operation**: Trucks slow down 7% on 5% upgrades, & speed up 5% on downgrades. (Figs. 3-25 through 3-30)
- **Two-lane roads**, 5%-grade for over 3 miles: → 1 HDT ≈ 15 PCs!
- **Question**: What can one do on steeply graded sections (downhill & up) to preserve safety?

EMERGENCY ESCAPE RAMPS

- Why do we use these? Who do these serve?
- Where should they be located? (4 conditions)

**Three basic types:**
1. **Gravity** (paved & sloped upward, relies on gravity)
2. **Sandpile** (sloped a bit upward & relying on a very high rolling resistance to slow the vehicle)
3. **Arrester Bed** (sloped in any direction; relies on loose aggregate)

?: Arrester beds are the most popular. Why?

Escape Ramp Location:

- Bottom of problem sections with good sight distance,
- In advance of significant curves,
- Before populated areas, &
- Right side of the road.

Identification of Problem Sections:

- On **new** roadways: Use **Grade Severity Rating System** (to avoid brake pad temperatures > 260°C)
- On **existing** roads: What/how, typically?
CLIMBING LAINES:

- Truck accident involvement increases significantly on UP-grades too.

- Capacity falls as heavy vehicles impede cars on significant &/or long upgrades → Bottleneck → Delay & reduced LOS

- Climbing lanes allow segregation of slow vehicles… → Improvements in safety, capacity, & LOS

PASSING LAINES & TURNOOUTS

- Passing lanes ≈ Climbing lanes, BUT used due to limited $d_p$ – rather than upgrades, truck slowdowns, & high opposing-traffic volumes.

- Turnouts also used, but require lead, slow vehicle to (practically) stop.

- Advance Signage is important for both → Use at points ~0.5 & 2 miles in advance (as well as at the actual location)

Passing Lanes:

- AASHTO recommends lengths ≥ 1000 ft & preferably 0.5 to 2 miles.

- Include every ~3 to 10 miles of impassable roadway.

- Add & drop with tapers of lengths:
  \[ L_{\text{add taper}} \geq 0.6WS \quad \& \quad L_{\text{drop taper}} \geq WS \]
  - where $W = ?$ & $S = ?$
**Turnouts:**

Common in (1) low-volume, mountainous terrain or (2) low-volume scenic areas where $P_{IDV} \geq 10\%$ (HDTs or RVs).

**?: Why not a *passing lane* in these situations?**

- Only use where sight distance is sufficient to anticipate turnout & re-enter safely (~1000’).
- Often unpaved, but should be smooth & firm.
- **Lengths** increase with speed: 200 ft @ 20 mph to 600 ft @ 60 mph = *Max.* (Exh. 3-68)

**In Summary:** What have we learned?

- What **benefits** do special lanes provide?
- What is the **difference** between *climbing* lanes & *passing* lanes?

**MIDTERM REVIEW**

**COURSE OBJECTIVES**

- Design of *Safe & Efficient* roadways.
- Familiarity with Roadway-Design *Standards*.
- Comfort with Computer-Aided *Highway Design* – On final exam

**COURSE TOPICS COVERED ON MIDTERM:**

- Design *Vehicle & Driver* Characteristics/Abilities
- Checking *Sight Distances*: Computing SSD, PSD, DSD
- Calculation of *Safe Radii* on HC’s (roll & slip) & *Clearance “M”* (for sight distance)
- *Developing Superelevation*: Runoff & Runout, $e_{run}$ vs. $e_{design}$ $s_{max}$ vs. $s_{actual}$ stationing of important points
- *Simple, Spiral & Compound Curves*: Geometric relationships
- *Vertical Curve* Geometry & *Special Lanes*
Example Midterm Exam Questions:

Geometric Design:
1. You wish to design a pair of simple, circular reverse 6-lane HCs in Texas, with $V_d = 60$ mph. $\Delta_1 = +60$ degrees, $\Delta_2 = -90$ degrees. What is the minimum distance that the PIs of these two curves need to be apart so no incompatibilities in the warping required for $e$ develop? (Assume NC = −2%).

2. You have an WB-50 vehicle navigating a 90-degree turn at an intersection (low speeds). Using Chapter 9, how long will the tangents be for a curve with tapers (from the PI to the points where the tapers hit the forward & back tangents)?

3. You wish to design a $v_d = 50$ mph, 6-lane spiral HC with a TS station of 11+30.00, $e_{max} = 7.5\%$, $e_{crown} = -2.5\%$, & $\Delta = 90^\circ$. $R_{min} =$ ?, $L_r =$ ?, $\Delta_l =$ ?, $d_{crown}$ @ 12+00 = ?

4. If this were a simple HC, where are key runoff/runout stations?

Other Questions:
• Circular Curves + Taper Geometry
• Spirals & Compound Curve Geometry
• Design Vehicles
• Special Lanes (& turnouts)

More Questions:
1. What is the length of removed curve edge on a $\Delta = 100^\circ$ asymmetric 15-foot radius curve with two tapers, one at 1:15 and the other at 1:20 with offsets of 2 feet & 3 feet?
Some Key Equations: HORIZ. ALIGNMENT

\[ d_{horiz} = \frac{x_2^2 - y_2^2}{2(a + g)R} \quad v_f^2 = \frac{e + f}{1 - ef} = \frac{V_s^2}{15R} \quad V_s^2 = \frac{e + y}{y - xe} \]

\[ L_{d, horiz} \sim 1.5 \quad L_{d, 2-lane} \quad L_{d, 6-lane} \sim 2 \quad L_{d, 2-lane} \]

\[ l_n = L_n - \frac{w_{cm} \cdot \Delta}{v_s^2} \]

Roadway Design Computations

Sight Distances + Horizontal Curves

Note: Arrows & variable lists are for standard calcs. All can be easily reordered & redirected!

T_r + \phi_r + V_d \rightarrow SSD

V_d \rightarrow PSD

SD + R ( + \Delta) \rightarrow M_{min}

V_d \rightarrow f_{max} + R \rightarrow e_d + W + N + \Delta_{spiral} \rightarrow L_v

Sta_{PC} + T \& L \rightarrow Sta_{PQ} \& Sta_{PT}

L_v + e_d + e_{0} \rightarrow L_i

L_s = L_i + R \rightarrow \Delta_2 + l \rightarrow \phi_2 + X_2 + Y_2 \quad \text{Spiral Transition}

R_{inner} (2) \rightarrow R_{outer} (1/3) \rightarrow \Delta_{1/3} + \Delta_2 + \rho_{1/3} \quad \text{CC Transition}
ROADWAY DESIGN Computations

Sight Distances + Vertical Curves

\[ T_r + a_s + V_d \rightarrow SSD \]
\[ V_o \rightarrow PSD \]
\[ G_1 \text{ & } G_2 \rightarrow A \]
\[ SD + A + h_{eye} + h_{obj} \rightarrow L_{\text{min,res}} \]
\[ SD + A + \beta + h_{lamp} \rightarrow L_{\text{min,sag}}^1 \]
\[ \text{Elev}_{VPC} + A + G_1 + L_{FC} \rightarrow \text{Elev}(x) \]

Note: Arrows & variable lists are for standard calcs. All can be easily reordered & redirected!