Task of Curve Driving

• Driver workload in curve driving task influenced by design elements:
  – Design consistency
  – Degree of curvature
  – Lane width
• Driver may benefit from:
  – Clearer roadway delineation
  – Wider lanes
  – Longer radius
  – Elimination of visual distractions

Source: NCHRP #600, p. 6-2
Curve Sharpness (Radius)

Radius – not the deflection angle – is most important

**Curve Driving Design Guidelines**

- Drivers have their highest visual demands and workload:
  - Just prior to curve entry
  - During curve entry
  - Curve negotiation
- Drivers attention is on:
  - Immediate roadway location
  - Guidance information

*Source: NCHRP #600, p. 6-2*
General Implications for Horizontal Curve Design

• Drivers need curve information primarily at curve beginning:
  – Don’t present complex information within
  • 250-350 ft of curve PC
  • 4-5 seconds of curve PC
  – Key negotiation and guidance information such as, lane markings and delineators should be clearly visible in peripheral vision, especially at night
  – Minimize distracting signage, advertisements, roadside scenery, foliage
  – Visual demands related to curve radius, not to deflection angle
    • Curve of $\geq 9^\circ$ ($\leq 605$ radius) are very demanding

Source: NCHRP #600, p. 6-2

Task Analysis for Curve Driving

• Driving tasks and constraints vary in intensity through the curve segments

Source: NCHRP #600, p. 6-2
Task Analysis for Curve Driving (cont)

- Information needs and important devices change throughout the curve

**Important information sources:**
- Curve "warning" sign and rider
- Pavement striping and edgelines
- Delineators
- Chevrons

Source: NCHRP #600, p. 6-2
Task Analysis for Spiraled Curve Driving

- With spiraled curves, drivers drive a fixed lateral distance from centerline, or edge, on the spiral and curve

Source: NCHRP #600, p. 6-2
Task Analysis for Spiraled Curve Driving

Key Driving Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Subtasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Approach</td>
<td>1.1 Locate bend</td>
</tr>
<tr>
<td></td>
<td>1.2 Get available speed information from signage</td>
</tr>
<tr>
<td></td>
<td>1.3 Make initial speed adjustments</td>
</tr>
<tr>
<td>2. Spiral Discovery (TS to SC)</td>
<td>2.1 Set vehicle at desired placement in lane</td>
</tr>
<tr>
<td></td>
<td>2.2 Follow centerline around spiral</td>
</tr>
<tr>
<td></td>
<td>2.3 Assess road conditions</td>
</tr>
<tr>
<td></td>
<td>2.4 Make additional speed adjustment</td>
</tr>
<tr>
<td>3. Curve Entry and Negotiation (SC to CS)</td>
<td>3.1 Adjust speed based on curvature and lateral acceleration</td>
</tr>
<tr>
<td></td>
<td>3.2 Maintain safe lane position</td>
</tr>
<tr>
<td>4. Exit (CS to ST)</td>
<td>4.1 Drive spiraled curve out</td>
</tr>
<tr>
<td></td>
<td>4.2 Maintain centered lane position</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 6-2

Spiral and Superelevation Transition on Simple Curve

Note: Driver’s $L_S = \text{Superelevation Runoff}$
Superelevation transition provides banking/superelevation where needed on simple curves

Profile:

Note: $f$ is sidefriction factor as lateral acceleration

Typical Superelevation Transition with Spiral

*Super runoff introduced over spiral length
Which is safer, simple curve design or spiraled curve design?

- California study next to Sierra foothills found higher crash rate on spiraled curves
  - Reason
    - Spiraled curves were on federal roads in National Forests and Parks
    - Drivers were familiar with simple curve design in the valley
- In general, no safety difference, as long as lane width accommodates drivers spiral for simple curves
Drivers Familiar with Simple Curve Design

• Where confronted with spiraled curve
  – Drivers look for beginning of curve (PC)
  – To drivers, appears to be around spiral midpoint
  – Driver begins a spiraled path about where spiral starts (TS)

Potential Driving Problems

• Very short spiral
  – Drivers expect spirals of adequate length for comfortable change in lateral acceleration
  – At end of spiral, on full curve, driver must make steering and speed adjustments (driver expects more spiral)

• Very long spiral
  – Spiral curvature keeps increasing, while driver thinks they are on a curve, but must correct speed and steering
Potential Driving Problems (cont.)

• Inadequate superelevation
  – Super is kept flat for log trucks, especially between curves, so log bunks are not stressed unduly
• Reverse curves without adequate distance between them for super runoff for each curve

Influence of Perception on Curve Driving

• The use of visual information to assess the curvature of an upcoming curve;
  – Apparent radius – the curve radius as seen from the drivers perspective
  – To select curve speed, drivers depend on;
    • Roadway features, primarily
    • Speed information from signs
• Primary design challenge for curve perception;
  – The “apparent radius” appears to be distorted flatter or sharper
  – Due to topography and other road elements
  – Combination curves of vertical curves superimposed on horizontal curves makes horizontal curve appear flatter

Source: NCHRP #600, p. 6-4
Influence of Perception on Curve Driving

Source: OSU Driving Simulator
Influence of Perception on Curve Driving (cont)

- Sag vertical curves on a horizontal curve gives an “apparent radius” that differs from reality;
  - The “apparent radius” is flatter
  - Can result in curve entry speeds that are faster than appropriate speed for actual horizontal curve

Source: NCHRP #600, p. 6-4
## Influence of Perception on Curve Driving (cont)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Effect</th>
<th>Empirical Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superimposed vertical sag</td>
<td>Makes a curve appear flatter</td>
<td>Strong</td>
</tr>
<tr>
<td>Superimposed vertical sag</td>
<td>For sag horizontal curves, the greater the cross slope and lane width, the greater the apparent flattening of horizontal curve</td>
<td>Analytical evidence</td>
</tr>
<tr>
<td>Superimposed vertical crest</td>
<td>Makes a curve appear sharper and may cause discontinuities in curve</td>
<td>Strong</td>
</tr>
<tr>
<td>Deflection angle</td>
<td>Holding radius constant, greater deflection angle makes the curve appear sharper, especially for smaller radii</td>
<td>Moderate</td>
</tr>
<tr>
<td>Spiral</td>
<td>May make curve appear flatter, or make curve perception more difficult, because the onset of curve is less apparent</td>
<td>Indirect</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 6-5
Influence of Perception on Curve Driving (cont)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Effect</th>
<th>Empirical Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delineators</td>
<td>Delineators provide drivers with more information to judge the curve radius, which improves accuracy of these judgments</td>
<td>Moderate</td>
</tr>
<tr>
<td>Signage</td>
<td>Drivers perceive curve as “riskier” if signs indicate that the curve is hazardous</td>
<td>Suggestive</td>
</tr>
</tbody>
</table>

Note: Should never indicate a curve is ‘hazardous’

Source: NCHRP #600, p. 6-5
• Shoulder rumble strips (SRS) are raised or grooved surfaces that provide:
  – Tactile/haptic warning – physical vibration
  – Auditory alert – sound
• Safety benefits:
  – Crash reductions of:
    • 21% on rural freeways
    • 18% on both urban and rural freeways
  – Reduce injury crashes by:
    • 7% - rural freeways
    • 13% - all freeways
  – Run-off-road crash rate reduction of up to 80% on rural freeways

Source: NCHRP #600, p. 16-6
Centerline Rumble Strips

- Effective countermeasure to eliminate
  - Head-on collisions
  - Opposite direction sideswipes
- Safety benefits
  - Reduces fatal and injury collision by
    - Rural two-lane roads, 45%
    - Urban two-lane roads, 64%
Rumble Strips (cont)

• Rumble strips need to generate 3-5 dBA above ambient sound levels to be effective

Source: NCHRP #600, p. 16-6

Rumble Strips (cont)

• Potential problems include:
  – Impact on bicyclists
  – Motorcycles have problems with grooved surfaces
  – Noise impact on surrounds

<table>
<thead>
<tr>
<th>Shoulder Width (ft)</th>
<th>Is there a Problem?</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1.9</td>
<td>No</td>
<td>Shoulder is too narrow for SRS or bicyclists.</td>
</tr>
<tr>
<td>2-3.9</td>
<td>Yes</td>
<td>Shoulder may be wide enough for SRS or bicyclists.</td>
</tr>
<tr>
<td>4-5.9</td>
<td>Yes</td>
<td>Shoulder may be wide enough for both SRS and bicyclists.</td>
</tr>
<tr>
<td>6+</td>
<td>No</td>
<td>Shoulder is wide enough for SRS and bicyclists.</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 16-7

• Rumble strips should not be used on a roadway shoulder unless a minimum clear path of 4 ft exists (MUTCD Section 6F.87)

Source: NCHRP #600, p. 16-7
An Oregon Example: Quantifying the Performance of Low-Noise Rumble Strips

Site Locations for Testing (© OpenStreetMap contributors)

Rumble Strips Tested

RS Comparison
Research Design

Site Selection Guidelines based on AASHTO SIP Method

- Site should be away from intrusive noises, like railroads, construction sites, or airports.
- No Reflecting Surfaces
  - Includes parked vehicles, signboards, buildings, guardrails, etc.
- Level & Straight
- Avoid Intersections or Ramps
- Homogenous Surface Condition & Type
- Free of Gravel or Debris

Exterior Sound Equipment Diagram

- Microphone Details
- Windscreen Mount
- Tripod
- Cable
- Laptop Interface
- Sound Analyzer
- Cross-Cable

Roadside Set Up:
- Exterior Sound Measurement
  - Use 100’ measuring tape, surveyor’s rod and level to locate Tripods
  - Personnel and Equipment should be behind 50’ microphone to avoid interference
  - Meteorological Equipment
    - Wind Sensor
    - Handheld Radar Gun
**Vehicles Tested**

- 2017 Ford Focus Hatchback
- 2015 Dodge Grand Caravan
- Striking the Sinusoidal RS
- Volvo VHD Dump Truck

**Rumble Strips Recorded**

RS Comparison

- Site A: Sinusoidal
- Site B: Rounded
**Exterior Sound Levels**

Roadside Setup

**Exterior Measurement: Average Observation**

![Sound Level Graph]

- STK 1
- STK 2
- STK 3
- Strike Average
- Baseline Average

Passenger Car Rounded RS

Time Series (~3 seconds)
**Exterior Measurement: RS Comparison**

Passenger Car Rounded & Sinusoidal RS

- **Rounded Strike**
- **Sinusoidal Strike**
- **Rounded Baseline**
- **Sinusodial Baseline**

**Time Series (~3 seconds)**

Delta Sound Level (dBA)  
- RVSHVRVanSVanRPCSPCR
  - 5.48
  - 3.07
  - 4.65
  - 2.21
  - 5.73

Delta = Strike dBA – Baseline dBA
**Exterior Measurement Comparison for Factor Groups**

- For the passenger car or van, the exterior noise measured at 25 and 50 ft from the roadside was less when striking the sinusoidal design compared to the rounded design. Both vehicles showed similar decreases in exterior sound, indicating that the sinusoidal design did in fact reduce roadside noise.
- Differences between vehicle types were expected, as the suspension, tire characteristics, and vehicle weight influence noise generation.
- Exterior measurements were made immediately adjacent to the roadway. Relationships between sound levels will be similar further from the road, but at a lesser intensity.

<table>
<thead>
<tr>
<th>RS Type</th>
<th>Roadside Delta Sound</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger Car</td>
<td>5.4 dBA</td>
<td>Clearly Noticeable ~5 dBA</td>
</tr>
<tr>
<td>Van</td>
<td>4.6 dBA</td>
<td></td>
</tr>
<tr>
<td>Sinusoidal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger Car</td>
<td>3.1 dBA</td>
<td>Noticeable 3 dBA</td>
</tr>
<tr>
<td>Van</td>
<td>0.2 dBA</td>
<td>Imperceptible 1 dBA</td>
</tr>
</tbody>
</table>

**And now, here’s**

![Image of a smiley face]
Effect of Marking Width

- Standard stripe width – most states use wider than 4-in stripe
  - Quality of pavement markings have high priority with drivers
- Wider lane stripes yield:
  - More centered lateral placement for vehicles
  - Fewer lane departures on curves
  - Improved lane keeping in low contrast conditions
- Wider striping is beneficial when:
  - Higher definition is needed, e.g., horizontal curves
  - Roads have narrow or no shoulder
  - Construction work zones

Source: NCHRP #600, p. 20-3

Effect of Lane Width

- A major benefit to safe operation on rural two-lane road

Expected Crash = Accident Frequency - 1.00

Example:
Exp. Crash Freq. = 1.30 - 1.00 = .30
30% in expected crashes for 10-ft lanes > 2000 veh/day

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 29
Operational Effects of Lane Widths on Freeway

**Effects of Lane Widths**

<table>
<thead>
<tr>
<th>Lane Width (ft)</th>
<th>Reduction in Free Flow Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.0</td>
</tr>
<tr>
<td>11</td>
<td>1.9</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
</tr>
</tbody>
</table>

**Combined Operation Effects of Lane & Shoulder Widths**

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 30
**Countermeasures to Improve Steering and Vehicle Control through Curves**

- Successful curve negotiations depends on:
  - Accurate steering
  - Speed control

- Countermeasure should:
  - Minimize lateral acceleration in lane
  - Maintain lane positioning
  - Maintain lateral control in curves

*Best countermeasure “control speed”*

Source: NCHRP #600, p. 6-8

---

**Design Speed**

AASHTO defines design speed as follows:

Design speed is a selected speed used to determine the various geometric features of the roadway. The assumed design speed should be a logical one with respect to the topography, anticipated operating speed, the adjacent land use, and the functional classification of the highway.

Design for design speed or post advisory speed if less.

Factors Influencing Vehicle Control through Curves

- Radius of curvature
- Speed
- Superelevation rate
- Coefficient of friction for surfacing
- Lateral acceleration
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Design guidelines
  - Curvature
    - Maximum allowable curvature (minimum radius) for design speed, i.e.,
    \[ R_{MIN} = \frac{V_{Des. spd.}^2}{15(e_{MAX} + f_{MAX})} \]
    
    \( e_{max} = 0.10 - 0.12 \) no snow or ice
    \( f_{max} = 0.10 \) @ 70 mph
    
    \( 0.08 \) – ice and snow
    \( 0.12 @ 60 \) mph
    
    \( 0.04 – 0.06 \) urban areas
    \( 0.14 @ 50 \) mph
    
    \( 0.06 \) – mountain passes
    \( 0.15 @ 40 \) mph
    
    \( 0.16 @ 30 \) mph
    \( 0.17 @ 20 \) mph

    *\( R_{MIN} \) relationship describes when all forces are in balance

Source: NCHRP #600, p. 6-8

Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Design guidelines
  - Superelevation
    - Should be designed to provide low lateral acceleration through the curve at design speed
    \[ e = \tan \theta \]
    \[ W\sin \theta + F = P\cos \theta \]
    \[ R = \frac{V_{Spd \ on \ Curve}^2}{15(e + f)} \]

Source: NCHRP #600, p. 6-9
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Remember
  - For vehicle on superelevated plane:

\[
F = m \times a
\]

\[
f \times W = \frac{W}{32.2} \times a
\]

\[
f = \frac{a}{32.2}
\]

Relation of side friction to lateral acceleration

Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Design guidelines
  - Superelevation
    - Designed to give acceptable lateral acceleration through the curve at design speed
    - Lateral acceleration, a, countered by f and vehicle weight acting down superelevated plane acceleration
    - Actually, a, according to AASHTO is:
      - Lateral accel \( a = f \times 32.2 \text{ ft/sec}^2 \), which is offset by f

Source: NCHRP #600, p. 6-8
Vehicle centered in lane at speed

Safety Effect from Superelevation Deficiency

<table>
<thead>
<tr>
<th>Superelevation Deficiency</th>
<th>AMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>.02</td>
<td>1.06</td>
</tr>
<tr>
<td>.03</td>
<td>1.09</td>
</tr>
<tr>
<td>.04</td>
<td>1.12</td>
</tr>
<tr>
<td>.05</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Expected crash frequency = AMF − 1.00

Example:
Exp. Crash Freq. = 1.09 − 1.00 = .09
or + 9%

Figure 4. Accident Modification Factor for Superelevation Deficiency for Rural Two-Lane

Source: FHWA-RD-99-207
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

• Design guidelines
  – Curvature
    • Minimize use of maximum allowable degree of curvature
    • Design all curves to achieve design speed, desirably
    • Driver must drive a “spiral path”, approximately, over superelevation transition length

Source: NCHRP #600, p. 6-8

Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

• Design guidelines
  – Spiral curves
    • Use spiral transition curves wherever possible, especially with high design speeds
    • Spiral curve lengths typically should provide 2-3 seconds travel time
    • Recommended curve radii with design speed of 50 mph is about 400-800 ft, or more, with spiral parameters of 0.33-0.5R
    • Spiral curves should provide adequate “superelevation runoff” length for comfortable superelevation transition

  (“Superelevation runoff” is road length from zero crown to full superelevation)

Source: NCHRP #600, p. 6-8
Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

- Design guidelines
  - Reverse curves
    - Do not use very short tangents between first curve exit and second curve entrance, this encourages a curved path through the tangent, i.e.,
      - 250 ft or less for two-lane highways
      - 450 ft or less for freeways
    - Desirably provide a length of tangents from end curve 1 to beginning curve 2 that provides part of super-runoff for curve 1 plus part of super-runoff curve 2
    - Or, provide a length equal to spiral for curve 1 plus spiral for curve 2 on ends of curve

Source: NCHRP #600, p. 6-8
Transitions between Two Simple Curves

Adequate tangent or spirals between reversing curves
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Design guidelines
  - Broken back curves
    - Avoid use of broken back horizontal curves, i.e., two curves in same direction with 500 ft or shorter tangent between
    - Violates driver expectancy
    - Drivers expect next curve to be in opposite direction
    - Visually unattractive

Source: NCHRP #600, p. 6-8
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

• Design guidelines
  – Design consistency
    • Avoid sharp isolated curves
    • Maintain consistency
      – Superelevation – provide needed superelevation for curve R design
      – Road width – usually, not changed except on very sharp curves with trucks, for off-tracking
    • Design all curves to achieve design speed, desirably

Source: NCHRP #600, p. 6-9
“Design consistency” refers to conformance of highways geometrics and operational features with driver expectancy
– Fewer driver errors with consistent geometric features and operation
– Driver expectancies:

<table>
<thead>
<tr>
<th>Problem Description</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers anticipate common upcoming situations and events</td>
<td>Roadway alignment and cross-sections are consistent</td>
</tr>
<tr>
<td>The more predictable the roadway, the less of problem</td>
<td>Curve speeds about the same and at design speed</td>
</tr>
<tr>
<td>Problems occur with surprises or inconsistent design or operation</td>
<td>Provide adequate sight distance to control features</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 16-8
**Design Consistency in Rural Driving (cont)**

- **Driver expectancies:**

<table>
<thead>
<tr>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers expect to have normal or standard situations</td>
</tr>
<tr>
<td>Abrupt narrowing of lanes or change in operation not expected, e.g., pedestrian, hikers, horse crossings, isolated signals</td>
</tr>
<tr>
<td>Roadway and environment upstream of a site creates expectancy for downstream conditions</td>
</tr>
<tr>
<td>Roadway features, speeds, roadside conditions, access points, cross-section will be same</td>
</tr>
<tr>
<td>Expectancies are associated with all driving tasks</td>
</tr>
<tr>
<td>Fine control – pavement surfacing and skid resistance consistent</td>
</tr>
<tr>
<td>Guidance – path selection, relative vehicle speeds, regulatory and warning information guide drivers behavior</td>
</tr>
<tr>
<td>Driver work-load compatible with a roadway of that class and volume</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 16-8

**Countermeasures to Improve Steering and Vehicle Control through Curves (cont)**

- **Pavement marking design guidelines**
  - Transverse stripes – painted or taped stripes applied perpendicularly to roadway to identify problem curves
    - Desirably stripes placed with decreasing spacing to encourage speed reduction
    - Effectiveness has been;
      - Mixed according to some studies
      - Some have shown no speed reduction and small increase
    - Most effective when implemented as rumble strips (see Markings Chapter, p: 20-4, 20-5)

Source: NCHRP #600, p. 6-11
Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

- Pavement marking design guidelines
  - Raised reflective pavement markers (RRPM)
    - Highly effective at improving curve visibility and reducing crashes
    - Especially effective in combination with marked centerlines and edge lines
    - Provides extra tactile cue to warn of lane encroachment
    - Effectiveness increases with Retroreflectivity
    - Place pairs of RRPM 800 ft in advance of sharp curve (≥12°) R=475 ft
    - Space markers at
      - 130 ft intervals on sharp curves
      - 250 ft intervals on flat curves
    - Use single RRPM’s on centerline edges for flatter curves
  
  *Effective to reinforce message

Source: NCHRP #600, p. 6-10
Combination of Striping & RRMP’s Very Effective

RRMP’s May Be Used Alone
Countermeasures to Prevent Crashes and Reduce Severity (cont)

- Allow recovery and minimize over-turning with safer side slopes/ditches
  - Safety side slope 6:1–10:1
  - Recoverable slope 4:1 or flatter
  - Non-recoverable slope 3:1–4:1
  - Critical slope steeper than 3:1, roll-over likely
- Remove/protect hazardous roadside obstacles
- Reduce severity of runoff-road crashes through improved roadside hardware and barrier/attenuation systems

Source: NCHRP #600, p. 8-4
Side Slope about 3:1  
Side Slope about 1:1

Use of Object Marker Preferable
Object Markers Provide

- Clear “message”
- Clear “warning”
- Defined “position”
- Provides “guidance”

Countermeasures to Allow Recovery, Prevent Crashes and Reduce Severity

- Install shoulder and/or centerline rumble strips (already covered)
- Widen two-lane roads and add narrow buffer median between opposing lanes
- Widen and pave shoulders
- Eliminate shoulder drop-offs
- Install median barrier for narrow medians on multilane roads

Source: NCHRP #600, p. 8-4
Widen 2-lane roads and add buffer medians

Wider Shoulders Improve Operations and Safety

• Shoulder width directly related to safety

Exp Crashes = AMF–1.0

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 37
Countermeasures for Shoulder Drop-offs

- Shoulders provide:
  - Additional maneuver room
  - Space for vehicles to stop in emergency or for texting
  - Lateral support for pavement subbase

- Shoulder drop-offs occur with a difference in height of a fraction of an inch to several inches between the pavement surface and the roadside surface

- Pavement drop-offs make recovery back onto roadway difficult

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 34
Pavement Drop-Offs on Curves Particularly Hazardous

Countermeasures for Shoulder Drop-offs (cont)

- Design guidelines

Source: NCHRP #600, p. 8-4
Driver Alertness on Long Tangent Sections

- Driver fatigue occurs on long tangents due to:
  - Reduced alertness and vigilance
  - Boredom
  - Reduce visual stimulation
  - Low physical driving demand

Source: NCHRP #600, p. 8-4
Operations on Grades

- Truck and other slow vehicles operate at lower speeds on steep upgrades
- Steep downgrades also create speed differential between trucks and cars
- Rear-end crashes, risky passing and sharp horizontal curves at grade bottom create hazard

Safety of Operations on Grades

<table>
<thead>
<tr>
<th>Grade (%)</th>
<th>Accident Modification Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
</tr>
<tr>
<td>4</td>
<td>1.07</td>
</tr>
<tr>
<td>6</td>
<td>1.10</td>
</tr>
<tr>
<td>8</td>
<td>1.14</td>
</tr>
</tbody>
</table>

* Expected Crash Frequency (decimal) = AMF – 1.00

Source: FHWA, “Expected Safety Performance”
Stopping Sight Distance (SSD)

- 100% SSD must be provided in roadway
  - Crest vertical curves alignment limits SSD
  - Sag vertical curves can be problematic if very short

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 53
**Stooping Sight Distance Profile**

Source: FHWA, Mitigation Strategies for Design Exceptions, 2007, p. 58

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**Preview Sight Distance and Grade Perception at Vertical Curves on Horizontal Curves**

- Preview sight distance (PVSD)
  - “the driver previews the roadway surface..., for vehicular control and guidance”
- Applies to horizontal curves
  - Near top of crest vertical curves
  - Near bottom of sag vertical curves
- \[ PVSD = S_T + S_C \]
  - \( S_T \) – driver’s PRT on road prior to PC
  - \( S_C \) - amount of horizontal curve needed to detect curvature

Source: NCHRP #600, p. 7-6
Preview Sight Distance and Grade Perception at Vertical Curves on Horizontal Curves

- PVSD – the distance traveled while driver perceives and reacts to upcoming curves
  - $S_T$ distance:
    - For simple curves
      - $S_T$ – the PRT should be on tangent section before PC
    - For spiraled curves
      - $S_T$ – the PRT can lie on spiral and previous tangent

*Some of deceleration takes place over $S_T$ distance with spirals*

Source: NCHRP #600, p. 7-7
Countermeasures to Improve Steering and Vehicle Control through Curves (cont)

- Pavement marking design guidelines
  - Provide the strongest curvature cues and short-range steering control (compensatory control)

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>General – post-mounted chevrons</td>
<td>Strongest guidance cues and short-range guidance (anticipatory control)</td>
</tr>
<tr>
<td>Treatment combinations</td>
<td>Superior effectiveness compared with individual treatments</td>
</tr>
<tr>
<td>Edge line / centerline</td>
<td>Strongest for curve recognition, curvature perception, and reduction of lateral variability. Discontinues in edge line aid in recognizing upcoming intersections, driveways, etc.</td>
</tr>
<tr>
<td>RRPM</td>
<td>Improving visibility of edge lines and centerlines. Reducing lane encroachments. Both visual and rumble effects provide encroachment cues.</td>
</tr>
<tr>
<td>Transverse stripes</td>
<td>Speed reduction. May be more effective at reducing higher (&gt;85th percentile) speed driving than lower speed driving.</td>
</tr>
<tr>
<td>&quot;SLOW&quot; text with arrow</td>
<td>Speed reduction and curve ahead warning.</td>
</tr>
</tbody>
</table>

*All have very positive effect, covered later

Preview Sight Distance and Grade Perception at Vertical Curves

- AASHTO Green Book has no design values for PVSD
- Daytime
  - Line of sight is from drivers eye, 3.5 ft
- Nighttime
  - Line of sight is from headlight, 2.0 ft

Criteria: Design values are valid only for values in table shown

Source: NCHRP #600, p. 7-7, Gattis & Duncan (1995)
Preview Sight Distance and Grade Perception at Vertical Curve (cont)

- Design guidelines

<table>
<thead>
<tr>
<th>Horiz Curve Radius (ft)</th>
<th>Required PVSD (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple Curve</td>
</tr>
<tr>
<td></td>
<td>A=328'</td>
</tr>
<tr>
<td>1312</td>
<td>430</td>
</tr>
<tr>
<td>1968</td>
<td>361</td>
</tr>
<tr>
<td>2624</td>
<td>325</td>
</tr>
<tr>
<td>3280</td>
<td>305</td>
</tr>
<tr>
<td>3936</td>
<td>289</td>
</tr>
<tr>
<td>4592</td>
<td>279</td>
</tr>
<tr>
<td>5248</td>
<td>272</td>
</tr>
<tr>
<td>5904</td>
<td>266</td>
</tr>
<tr>
<td>6560</td>
<td>262</td>
</tr>
</tbody>
</table>

* Minimum value
** Maximum value

PVSD – PREVIEW SIGHT DISTANCE: A view of the pavement surface, alignment and other features that provide vehicle control and guidance cues

$S_T$ – drivers reaction distance prior to the PC of the horizontal curve

$S_C$ – amount of the horizontal curve required to make the curve detectable

* Modeled at 60 mph

Source: NCHRP #600, p. 7-7
Example
Given: 1600’ vertical curve with grades of +1.5% and -1.5% simple curve of 2624’ radius that coincides with crest vertical curve

Preview Sight Distance:
$PVSD = S_T + S_C$
$PVSD = 325 + 230 = 555’$

Vertical Offset:
$Offset = \frac{1}{2} \sqrt{\frac{1}{2} \left(\frac{(G_2 - G_1)}{100(L)}\right) (SD)^2}$
$Offset = \frac{1}{2} \sqrt{\frac{1}{2} \left(\frac{(1.5 - (-1.5))}{100(1600)}\right) (611)^2}$
$3.5 = \frac{1}{2} \left(\frac{(1.5 - (-1.5))}{100(1600)}\right) (611)^2$
$SD = 611’ > 555’ PVSD – curve is visible

Note: if LVC = 1200’
$3.5 = \frac{1}{2} \left(\frac{(1.5 - (-1.5))}{100(1200)}\right) (SD)^2$
$SD = 529’ < 555’ PVSD – curve not visible; use delineators
Out of control trucks typically caused by:
- Losing brakes from overheating
- Mechanical loss of braking

Truck escape ramps slow vehicles by:
- Gravitational deceleration, upgrades
- Rolling resistance, pea gravel
- Both

Source: NCHRP #600, p. 7-5

Design guidelines
- Geometric
  - Design so driver can see entire ramp (or much of it)
  - Clearly distinguish escape ramp from service road
  - Truck drivers typically opt for the last ramp of two on grade
  - Insure mainline traffic can’t use the ramp by mistake
  - Steering ability is lost on the ramp, so should be straight and flat angle departure

Source: NCHRP #600, p. 7-4
Geometrics and Signing for Truck Escape Ramps (cont)

• Design guidelines
  – Signing
    • Advance signing is critical
    • "Runaway Vehicles Only" and "No Parking" signs at ramp entry so ramp is not blocked by other vehicles
    • Weight specific speed signs should limit to 5 weight classes
    • Minimal, standard or briefing signs had to underestimate severity on server grades and over-estimate on benign grades

Source: NCHRP #600, p. 7-4
Spiral Parameter – Spiral Curves

\[ A = \sqrt{LR} \]
\[ A = 0.5R \]
\[ LR = 0.5R \]
\[ L = 0.25R^2 \]
\[ L_s = 0.25 \times 400 = 100 \text{ w/R = 400'} \text{ or } 0.25 \times 800 = 200 \text{ w/R = 800'} \]

Spirals are designed to match drivers' natural steering behavior, with a gradual increase in centrifugal force that facilitates superelevation transitions. The superelevation and downward weight component of the vehicle match the increase in centrifugal force. This improves the vehicle's lateral stability. However, overly long spirals can lead to:

- Misleading perception of curve sharpness
- Inappropriate entry speed
- Unexpected steering and speed corrections within the curve

Most desirable spiral length is the distance traveled during steering time, i.e., 2-3 sec.

2 sec - \[ L_s = 1.47 \times (50)^2 = 147' \]
3 sec - \[ L_s = 1.47 \times (50)^3 = 220' \]
Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

• Pavement marking design guidelines
  – Use pavement markings to improve curve driving, curve detection and driver performance
  – Typically, use surface markings characterized by;
    • Long dashes
    • Short gaps
    • Short repetition cycles
  – Use combination of treatments to increase effectiveness

Source: NCHRP #600, p. 6-10

Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

• Pavement marking design guidelines (cont)
  – Centerline
    • Use widest possible centerline to maximize visibility
      – 4” width minimum
      – 6” width, more effective
      – 8” width, no more effective than 6”
    • Use highly retroreflective materials
  – Edge lines
    • Must use on roadways ≥20 ft and ADT ≥6000 vpd on narrow roads
    • Use near major crossing roadways and major driveways
    • Use by policy
  – Bicycle lane line
    • Must be 8” continuous white stripe, ODOT

*Note: Shall use centerline on continuous 20 ft roadways with ADT ≥6000 vpd (MUTCD). May use centerline on roadways ≥16 ft in width. May use either on narrow roadways.

Source: NCHRP #600, p. 6-10
Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

- Pavement marking design guidelines
  - “Slow” text with pavement arrow
  - Use on pavement about 250 ft before curve

Note: “Slow” is not a standard legend for pavement markings or signs according to MUTCD. Should always be used with the “reason” to “slow”

Source: NCHRP #600, p. 6-10

Countermeasures for Improving Steering and Vehicle Control through Curves (cont)

- Pavement marking design guidelines
  - Combination of treatments – much more effective, especially where rumble strips are used
    - Improves:
      - Curve recognition
      - Lane position
  - Number of encroachments
    - Transverse stripes and widening of inside edge markings have an effect on high speed drivers
      - Provides an effective treatment at hazardous locations

Source: NCHRP #600, p. 6-11
Signs on Horizontal Curves

- Sign information should be concise and efficient so drivers can:
  - Process the information
  - Alter their speed
- Advance warning signs research efforts differ on most effective means:
  - Text vs symbols
  - Sign placement
  - Sign message
  - Relevant curve radii
  - Driver population

Source: NCHRP #600, p. 6-12

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Signs on Horizontal Curves (cont)

- Warning signs for curves should be placed to give adequate PRT

Source: MUTCD p. 108

Note: criteria in MUTCD differs slightly from NCHRP #600
**Signs on Horizontal Curves (cont)**

- Use of chevron signs outside curves to provide additional guidance

Note: Criteria in MUTCD slightly different than NCHRP #600, HFG

Source: MUTCD p. 113

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**Design Guidelines for Turnouts on Grade**

- Turnouts provide unobstructed shoulder areas that allow slow moving vehicles to pull out of the through lane
  - Turnout entry
    - Signage
  - Use signs to:
    - Notify of upcoming turnouts
    - Notify of specific turnouts
    - Remind of legal requirements for use; any vehicle slowing other vehicles
    - Locate beginning of turnout and provide turnout sign
    - Provide advance sign and place 500-800 ft ahead
    - Use upward sloping arrow (MUTCD R4-14) to encourage vehicle to move right
Design Guidelines for Turnouts on Grade (cont)

- Turnout entry (cont)
  - Sight distance
    - Adequate sight distance to allow adequate deceleration time
    - Avoid locating adjacent to horizontal or vertical curves that limit sight distance
    - Available sight distance should be 1000 ft to turnout entrance
  - Entry speeds
    - Approach speeds vary with grade and horizontal alignment
    - Downgrades and gentle curves require longer turnouts
    - Avoid turnouts above high fills or dropoffs

Source: NCHRP #600, p. 7-2
Design Guidelines for Turnouts on Grade (cont)

• Turnout entry
  – Lengths
    – Vehicles enter turnouts of speeds up to 50 mph, should be able to decelerate to stop
    – Turnouts with short lengths of 200 ft are not used, according to one study
    – Turnouts that are too long can be used as passing lane
    – Low speed roads (≤30 mph); Turnouts of 200-250 ft, SSD_{30} = 200 ft
    – High speed roads (50 mph); Turnouts of 400-450 ft suitable, SSD_{30} = 425 ft

• Turnout exit
  – Locate turnouts with adequate sight distance for approaching drivers to slow to speed of exiting vehicle

Source: NCHRP #600, p. 7-2

Design Consistency in Rural Driving (cont)

• Factors that should be reviewed for consistency:

<table>
<thead>
<tr>
<th>Geometrics</th>
<th>Horizontal and vertical alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sight distance</td>
<td>Must have 100% SSD</td>
</tr>
<tr>
<td>Warning &amp; regulatory signs</td>
<td>Higher priority, formal information</td>
</tr>
<tr>
<td>Cross-section markings</td>
<td>Critical for visual, auditory, vibrational cues</td>
</tr>
<tr>
<td>Signals</td>
<td>Adequate sight distance and prior warning</td>
</tr>
<tr>
<td>Road surface and type</td>
<td>Provide adequate skid resistance</td>
</tr>
<tr>
<td>Guide signs and route markers</td>
<td>Provide navigational needs, should not confuse with GUIDANCE</td>
</tr>
<tr>
<td>Lighting</td>
<td>Use where needed for special sites</td>
</tr>
</tbody>
</table>

Source: NCHRP #600, p. 16-8