Improving Safety of Horizontal Curves

Resource Center
Safety & Design National Technical Services Team
Federal Highway Administration
### Improving Safety of Horizontal Curves Workshop

#### Outline and Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:45 am</td>
<td>Registration. Workshop Participants are requested to bring calculators capable of scientific notation calculations.</td>
</tr>
<tr>
<td>8:00 am</td>
<td><strong>Introduction and Background</strong> – Session 1 (Slides 1-42)</td>
</tr>
<tr>
<td></td>
<td>Overview of Roadway Departure and Horizontal Curves Safety</td>
</tr>
<tr>
<td></td>
<td>25% of total highway fatalities occur in horizontal curves. Information is provided on roadway departure and horizontal curve crash characteristics. The objective of the workshop are described to reduce the incidence of horizontal curve crashes through application of the latest design and safety and operations best practices with an emphasis on rural two-lane highway curves.</td>
</tr>
<tr>
<td></td>
<td>Workshop participants will be requested to present their situations, which they are currently seeking to address; these situations will be discussed in detail and candidate countermeasures identified in the final workshop session</td>
</tr>
<tr>
<td>8:50 a.m.</td>
<td>Break</td>
</tr>
<tr>
<td>9:00 am</td>
<td><strong>Prediction of Safety Performance for Rural Two-Lane Highways</strong> – Session 2 (Slides 1-39)</td>
</tr>
<tr>
<td></td>
<td>Models for Predicting the Safety Performance of Rural Two-Lane Highway Segments are presented. Example calculations are provided and application of the crash prediction equations is made.</td>
</tr>
<tr>
<td>9:40 am</td>
<td><strong>Prediction of Safety Performance for Horizontal Curves</strong> – Session 3 (Slides 1-19)</td>
</tr>
<tr>
<td></td>
<td>Models for Predicting the Safety Performance of Horizontal Curves on Rural Two-Lane Highway Segments are presented. Example calculations are provided and application of the crash prediction equations is made.</td>
</tr>
<tr>
<td>10:05 a.m.</td>
<td>Break</td>
</tr>
<tr>
<td>10:15 a.m.</td>
<td><strong>Horizontal Curve Exercise</strong> – Session 3X (slides 1 – 14) + Student Worksheet</td>
</tr>
<tr>
<td></td>
<td>The crash prediction equations for rural two-lane highways and horizontal curves are applied to route 468. The groups will calculate the number of crashes per year for a two-lane rural highway and a horizontal curve of the same length on that highway. The workshop as a whole will discuss the predicted number of crashes.</td>
</tr>
<tr>
<td>10:50 a.m.</td>
<td><strong>Measures to Reduce Horizontal Curve Crashes</strong> – NCHRP 500 Volume 7 – Session 4 (Slides 1-49)</td>
</tr>
<tr>
<td></td>
<td>The 20 strategies of the AASHTO Strategic Plan 17-18 (3) - NCHRP 500 Volume 7 A Guide for Reducing Collisions on Horizontal Curves are presented.</td>
</tr>
<tr>
<td>11:55 a.m.</td>
<td>Lunch</td>
</tr>
</tbody>
</table>
Improving Safety of Horizontal Curves Workshop
Outline and Schedule

1:00 p.m.  Pavement Countermeasures for Reducing Roadway Departure Crashes – Session 5 (Slides 1-104)

2:10 p.m.  Break

2:20 p.m.  Signing and Markings Countermeasures for Horizontal Curves – Session 6 (Slides 1-32)

2:50 p.m.  Break

3:00 p.m.  Reducing the Consequences of Leaving the Roadway – Session 7 (Slides 1-45)

3:50 p.m.  Break

4:00 pm  Case Studies and Deployment Strategies - Session 8 (Slides 1-49)

4:45 p.m.  Workshop Closure and Summary
           Feedback/Participants Surveys
Improving Safety of Horizontal Curves

58th Traffic Engineering & Safety Conference
October 21, 2009
Fred Ranck and Ken Wood

Self Introductions

• Name and Agency/Office
• Discipline
• What would like to know more about in regard to Horizontal Curves?
Housekeeping Items

• Start/Quit Times
• Breaks
• Lunch
• Cell Phones Off! (or Silent/Vibrate)
• Ask Questions/ Share Experiences

Agenda

• Session 1 - Introduction
• Session 2 – Prediction of Safety Performance for Two-Lane Rural Highways & Highway Safety Manual
• Session 3 – Geometric Design and Prediction of Safety Performance of Horizontal Curves
• Session 4 – Measures to Reduce Horizontal Curve Crashes
• Session 5 – Pavement Countermeasures
• Session 6 - Signing, Lighting and Delineation Countermeasures
• Session 7 - Reducing Consequences of leaving the road – Slopes, Ditches, & Hardware
• Session 8 - Case Studies & Deployment Strategies
Session 1 Learning Outcomes:

- Present national crash statistics
- Describe the relationship of horizontal curves on crash rates
- Introduce NCHRP 500 Series Volumes
- Identify difference between Nominal & Substantive Safety

Introduction

Figure 1: Fatalities and Fatality Rates per 100 Million VMT From 1961 - 2008
Fatality rates

**Future Safety Vision**

- Rate = 1.41 (68,000)
- Rate = 1.0 (48,000)
- Rate = .41 (20,000)

**2005 - 2007 Fatal Crashes**

**Yearly Averages**
**Crash Costs**

**Cost of All Crashes in U.S. (Year 2007)**
- $300 Billion
- $1070 for every person in the U.S.
- 2.8% of the GDP

---

**Crash Cause By Factor**

- **Roadway**: 34%
  - 3%
  - 1%
- **Driver**: 93%
  - 57%
  - 27%
  - 3%
- **Vehicle**: 12%
  - 6%
  - 2%
Rural Non-Interstate Safety

Rural Non-Interstate Fatality Rates are the 800-lb Gorilla of Highway Safety

- Fatal Accidents
- Injury Accidents
- Total Accidents

<table>
<thead>
<tr>
<th>Roadway Function Class</th>
<th>RURAL</th>
<th>URBAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Lanes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 or more lanes, divided subtotal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Lanes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 or more lanes, undivided</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeway</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Accident Rates by Facility Type

Accident Rate Varies Significantly by Type of Road, Location and Other Factors
2007 National Fatal Crashes

37,248 Fatal Crashes
19,753 Roadway Departures

Roadway Departure Crash - A non-intersection crash in which a vehicle crosses an edge line, a centerline, or otherwise leaves the traveled way.


Yearly Average – 20,135
Improving Safety of Horizontal Curves

2005-2007 Horizontal Curve Fatal Crashes

Yearly Average – 10,295

Percentage of Fatal Crashes in Horizontal Curves

2005-2007 Average – 27%
Horizontal Curves and Safety

Approximately 27% of fatal crashes occur along horizontal curves.

Average crash rates for horizontal curves is about 3 times that of tangent segments.

Source: Glennon, et al, 1985 study for FHWA.
Horizontal Curves and Safety

Curve Crash Rates:
• for Radii > 2,500 ft are approximately equal to crash rate on tangent
• 2X for Radii of 1,000 ft
• 8X for Radii of 500 ft
• FHWA/TX-07/0-5439-1 TTI Research

Follow up Study of more than 200 curves on MnDOT and County routes found:
• Crash rates on curves with radii greater than 2,000 feet were approximately equal to the overall rate of tangent sections
• 90% of fatal crashes and 75% of injury crashes occurred on curves with Radii less than 1,500 feet
• as curve Radii decrease, crash rate increases:
  - 2X at 1,500 feet
  - 5X at 1,000 feet
  - 11X at 500 feet
• Howard Preston, CH2M Hill for Minnesota
NCHRP 500 Reports

- Series of reports developed to assist states implement their Strategic Highway Safety Plans

- NCHRP Report 500 Volume 7 - "A Guide for Reducing Collisions on Horizontal Curves"

Objectives and Strategies for Improving Safety at Horizontal Curves

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2 A</td>
<td>Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve</td>
</tr>
<tr>
<td>10.2 B</td>
<td>Minimize the adverse consequences of leaving the roadway at a horizontal curve</td>
</tr>
<tr>
<td>10.2 C</td>
<td>Improve safety features surrounding the horizontal curves</td>
</tr>
<tr>
<td>10.2 D</td>
<td>Improve visibility for drivers</td>
</tr>
<tr>
<td>10.2 E</td>
<td>Enhance traffic flow</td>
</tr>
<tr>
<td>10.2 F</td>
<td>Increase driver awareness</td>
</tr>
<tr>
<td>10.2 G</td>
<td>Improve pedestrian safety</td>
</tr>
<tr>
<td>10.2 H</td>
<td>Reduce vehicle speeds</td>
</tr>
<tr>
<td>10.2 I</td>
<td>Improve drainage and pavement conditions</td>
</tr>
<tr>
<td>10.2 J</td>
<td>Enhance sign visibility</td>
</tr>
<tr>
<td>10.2 K</td>
<td>Improve road geometry</td>
</tr>
</tbody>
</table>

1-11 Improving Safety of Horizontal Curves
Link Between Standards and Safety

- How can we make highways sufficiently safe?
- Does applying standards achieve it?
- How about cost-benefit?
- What can road professionals do?

Two Ways to Look at Safety

- **Nominal Safety** is examined in reference to compliance with standards, warrants, guidelines and sanctioned design procedures
- **Substantive Safety** is the expected crash frequency and severity for a highway or roadway
Aspects of Nominal Safety

– Roadway design must enable road users to behave legally
– Roadway design should not create situations with which a minority of road users have difficulties
– Owning agency requires protection against claims of moral, professional and legal liability

AASHTO Policies and State design manuals

= Safe Design Practices represent “safe” design practice in the minds of many

The often unasked questions are:

Is a road designed to meet current standards as safe as it can be?
Is a road designed to meet current standards as safe as it should be?
Is this curve “safe”? 

Design Speed on Tangent = 60 mph

*Sharp Curve after long Tangent*

- Curve Design Speed of 35 mph is acceptable and provided for in AASHTO Policy

Substantive safety is the performance of the road as measured in terms of crashes, including their frequency, type and severity.

- A function of what resources are available (roadway design, maintenance, enforcement, emergency medical services)

- A function of the “context” of the location
“Substantive” and “Nominal” Safety

Conventional Wisdom        New Approach

Nominal Safety "Safety Linkage" Substantive Safety

Substantive Safety is “Context Sensitive”

What types, frequency and severity of crashes would you expect here?

Would they be different for the two roadways?
Issues – when considering the relationship between nominal and substantive safety

- What is the basis for the design and operations values referred to in criteria?
- How do we apply the values in actual design and operation?
- What factors beyond the control of the design/operations engineers influence safety?
- How much do we really know about the relationship of highway infrastructure and operations features to safety?

Session 1 Review:

- The rate of crashes on horizontal curves is approximately ____ times the rate on tangents.

Source: Glennon, et al, 1985 study for FHWA
Session 1 Review:

- In the United States, what percent of fatal crashes occur on horizontal curves?

Session 1 Review:

- Compared to Nominal Safety, ________________ is the expected crash frequency and severity for a highway or roadway.
Questions and Discussion
Session 2

Prediction of Safety Performance for Rural 2-Lane Highways

IL Route 125 approaching Ashland, IL

Session 2 Learning Outcomes:

• Describe the Crash Prediction Equations (SPF) for Two-Lane Rural Highway Segments
• Describe Accident Modification Factors (AMF’s) for Two-Lane Rural Highway Segments
Predicting Safety Performance of Rural 2-Lane Highways

How Can A Crash Prediction Be Used?

- Program level - Prioritize segments or locations for selection of projects

- Project Level –
  - Assess the relative needs for a project
  - Communicate the relative needs to public
  - Prioritize work to keep project within budget
  - Justification for design exceptions

- Tort Defense – if used properly, this tool can help quantify the relative safety of a facility and demonstrate that an agency is addressing safety needs appropriately.
Accident prediction model made up of 2 components:
- Safety Performance Function (SPF) model for base conditions
- Accident Modification Factors (AMF)
  - Adjust SPF prediction for actual, or proposed, conditions

Base condition model is a function of exposure (ADT) and length of segment (miles)

\[ N_{spf-rs} = (ADT_n) (L) (365) (10^{-6}) e^{-0.312} \]
\[ = (ADT_n) (L) (365) (10^{-6}) (0.7320) \]
### Predicting Safety Performance of Rural 2-Lane Highways – Example:

\[ N_{spf-rs} = (ADT_n) (L) (365) (10^{-6}) e^{-0.312} \]

2-lane secondary state highway connecting a US marked route to a primary State marked route in a rural county of 25,000 population;

Where:
- ADT = 3,500 vpd
- Length = 26,485 feet = 5.02 miles

\[ N_{spf-rs} = (3,500) (5.02) (365) (10^{-6}) e^{-0.312} = (3,500) (5.02) (365) (10^{-6}) (0.7320) = 4.69 \text{ crashes per year} \]

### Safety Performance Function (SPF) for Base Crash Prediction – Example:

Where:
- ADT = 3,500 vpd
- Length = 26,485 feet = 5.02 miles

\[ N_{spf-rs} = (ADT_n) (L) (365) (10^{-6}) e^{-0.312} \]

\[ N_{spf-rs} = (3,500) (5.02) (365) (10^{-6}) e^{-0.312} = (3,500) (5.02) (365) (10^{-6}) (0.7320) = 4.69 \text{ crashes per year} \]
Safety Performance Function (SPF) for Base Crash Prediction—Exercise:

Where:
- ADT = 5,500 vpd
- Length = 32,740 feet = 6.2 miles

\[
N_{spf-rs} = (ADT_n) (L) (365) (10^{-6}) e^{-0.312}
\]

\[
N_{spf-rs} = (5,500) (6.2) (365) (10^{-6}) e^{-0.312}
\]

\[
N_{spf-rs} = (5,500) (6.2) (365) (10^{-6}) (0.6148)
\]

= ? crashes per year

Accident Modification Factors (AMFs)

- Account for difference between base and actual geometry
- Estimate effects of individual geometry elements on safety
- Can be greater or less than 1:
  - < 1.0 -- lower crash frequency
  - > 1.0 -- increased crash frequency

\[
1 - AMF = CRF
\]
Predicting Safety Performance of Rural 2-Lane Highways

- Accident Modification Factors (AMF's)

$$N_{predicted-rs} = N_{spf-rs} \times (AMF_{1r} \ldots AMF_{12r}) \times C_r$$
AMF for Lane Width

AMF_{ra} for lane width

- ‘Base condition’ is 12-ft lanes
- AMFs for ADT >2000 based on Zegeer
- AMFs for ADT <400 based on studies by Griffin and Mak
- Expert panel developed transition lines, referencing other research

Crash Modification Factors - Lane Width Additional Info

* Note equations for ADT’s between 400 and 2000
**AMF - Adjustment for Related Crashes**

Adjust for (Run off Road + Head-on + Sideswipes) to total crashes

\[ p_{ra} = 0.574 \]

\[ AMF_{1r} = (AMF_{ra} - 1.0) p_{ra} + 1.0 \]

**Calculation for Lane Width (AMF_{1r}): Example**

For: 3,500 ADT for a 10 foot wide lane:

From Exhibit 10-14: \( AMF_{ra} = 1.30 \)

\[ AMF_{1r} = (AMF_{ra} - 1.0) p_{ra} + 1.0 \]

\[ = (1.30 - 1.0) \times 0.574 + 1.0 \]

\[ = (0.30) (0.574) + 1.0 \]

\[ = 0.172 + 1.0 = 1.172 \]
AMF for Shoulder Width

Base condition is 6-ft shoulders

- AMFs for ADT >2000 based on Zegeer (FHWA)
- AMFs for ADT <400 based on other studies by Zegeer (NCHRP 362)
- Expert panel developed transition lines, referencing other research
- For higher ADT’s, 2.8% reduction in crashes per foot of shoulder widening

\[
AMF_{2r} = (AMF_{wra} AMF_{tra} - 1.0)P_{ra} + 1.0
\]

Exhibit 10-15: AMF for Shoulder Width on Roadway Segments (AMF_{wra})

<table>
<thead>
<tr>
<th>Shoulder Width</th>
<th>AADT (vehicles per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 400</td>
</tr>
<tr>
<td>0-ft</td>
<td>1.10</td>
</tr>
<tr>
<td>2-ft</td>
<td>1.07</td>
</tr>
<tr>
<td>4-ft</td>
<td>1.02</td>
</tr>
<tr>
<td>6-ft</td>
<td>1.00</td>
</tr>
<tr>
<td>8-ft or more</td>
<td>0.98</td>
</tr>
</tbody>
</table>

* Note equations for ADT’s between 400 and 2000
### AMF for Shoulder Type

**Exhibit 10-18: Accident Modification Factors for Shoulder Types and Shoulder Widths on Roadway Segments (AMF<sub>ra</sub>)**

<table>
<thead>
<tr>
<th>Accident type (Severity)</th>
<th>Shoulder type</th>
<th>AMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-vehicle run-off-road accidents and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe collisions (Unspecified)</td>
<td>Paved</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>Turf</td>
<td>1.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shoulder width (ft)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Gravel</td>
<td>1.00</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
<td>1.02</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>Composite</td>
<td>1.01</td>
<td>1.02</td>
<td>1.02</td>
<td>1.03</td>
<td>1.04</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td>Turf</td>
<td>1.01</td>
<td>1.03</td>
<td>1.04</td>
<td>1.05</td>
<td>1.08</td>
<td>1.11</td>
<td>1.14</td>
</tr>
</tbody>
</table>

**NOTE:** The values for composite shoulders in this exhibit represent a shoulder for which 50 percent of the shoulder width is paved and 50 percent of the shoulder width is turf.

### AMF for Shoulder Width

**Exhibit 10-17: Default Distribution by Collision Type for Specific Crash Severity Levels on Rural Two-Lane Two-Way Roadway Segments.**

- Adjust for (Run off Road + Head-on + Sideswipes) to total crashes

\[
\text{AMF}_{2r} = (\text{AMF}_{wra} - 1.0) \cdot \text{pra} + 1.0
\]

- \( \text{pra} = 0.574 \)
AMF for Shoulder Width

For: 3,500 ADT with a 2 ft wide aggregate shoulder:

\[ AMF_{wra} = 1.30 \text{ (Exh 10-16)} \quad \text{and} \quad AMF_{tra} = 1.01 \text{ (Exh 10-18)} \]

Adjustment from crashes related to lane and shoulder width (Run off Road + Head-on + Sideswipes) to total crashes using default value for \( p_{ra} = 0.574 \)

\[
AMF_{2r} = (AMF_{wra} AMF_{tra} - 1.0) p_{ra} + 1.0
\]

\[
= ((1.30)(1.01) - 1.0) * 0.574 + 1.0
\]

\[
= (0.313)(0.574) + 1.0
\]

\[
= 0.180 + 1.0 = 1.180
\]

Safety Effects of Lane and Shoulder Width – Example:

- For 1,500 ADT 10' lane and no shoulder: What is \( AMF_{1r,2r} \)?
  - Lane Width = 10' (From Exhibit 10-14) \( AMF_{ra} = 1.213 \)
  - \( AMF_{1r} = (1.213 - 1.0) x 0.574 + 1.0 = 1.122 \)
  - Shoulder Width = 0' (From Exhibit 10-16) \( AMF_{wra} = 1.375 \quad AMF_{2r} = (((1.375 x 1.00) - 1.0) x 0.574) + 1.0 = 1.215 \)

\[
\text{total AMF}_{1r,2r} = 1.122 \times 1.215 = 1.364
\]
Safety Effects of Lane and Shoulder Width – Example:

• For 1,500 ADT 10’ lane and no shoulder: What is AMF?
  • Lane Width = 10’ From Exhibit 10-14: Calculated AMF_{ra} = 1.213 and p_{ra} is assumed to be 57.4% 
    AMF_{1r} = (1.213-1.0) \times 0.574 + 1.0 = 1.122 
  • Shoulder Width = 0’ From Exhibit 10-16: Calculated AMF_{wra} = 1.375 and p_{ra} is assumed to be 57.4% 
    AMF_{2r} = (1.375 \times 1.00-1.0) \times 0.574 + 1.0 = 1.215 
    AMF_{1r&2r} = 1.122 \times 1.215 = 1.364 

Safety Effects of Lane and Shoulder Width – Example:

• For 2,500 ADT and 11 foot lane and a 4 foot aggregate shoulder, what is AMF?
  • Lane Width = 11’ AMF_{ra} = 1.05 
    AMF_{1r} = (1.05-1.0)(0.574) + 1.0 = 1.029 
  • Shoulder Width =4’ AMF_{wra} = 1.15 
    AMF_{2r} = ((1.15 \times 1.01)-1.0)(0.574)+1.0 = 1.093 
  • Shoulder type AMF_{tra} = 1.01 
    Total AMF_{1r&2r} = AMF_{1r} \times AMF_{2r} 
    = 1.029 \times 1.093 = 1.124
Prediction of Safety Performance for
Rural 2-Lane Highways

**AMF for Grade**

<table>
<thead>
<tr>
<th>Approximate Grade (%)</th>
<th>Level Grade (≤ 3%)</th>
<th>Moderate Terrain (3% &lt; grade ≤ 6%)</th>
<th>Steep Terrain (&gt; 6%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>1.10</td>
<td>1.16</td>
</tr>
</tbody>
</table>

**AMF for Driveway Density**

\[
AMF_{DD} = \frac{0.322 + (0.05-0.005\times\ln(ADT))\times DD}{0.322 + (0.05-0.005\times\ln(ADT))\times 5}
\]

Where:
- DD = Driveway Density (Driveways per mile)
- ADT = Average Daily Traffic

Improving Safety of Horizontal Curves 2-13
AMF for Installing Centerline Rumble Strips (AMF\textsubscript{7r})

Exhibit 13-55: Potential Crash Effects of Installing Centerline Rumble Strips

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Setting (Road type)</th>
<th>Traffic Volume (AADT)</th>
<th>Accident type (Severity)</th>
<th>AMF</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Install centerline rumble strips</td>
<td>Rural (Two-lane)</td>
<td>5,000 to 22,000</td>
<td>All types (All severities)</td>
<td>0.86</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All types (Injury)</td>
<td>0.85</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Frontal and opposing-direction sideswipe (All severities)</td>
<td>0.79</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Frontal and opposing-direction sideswipe (Injury)</td>
<td>0.73</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Base Condition: Absence of centerline rumble strips.

NOTE: Based on centerline rumble strip installation in seven states: California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington

AMF for Passing Lanes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Setting (Road type)</th>
<th>Traffic Volume</th>
<th>Accident type (Severity)</th>
<th>AMF</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide passing lane or climbing lane</td>
<td>Rural (Two-lane)</td>
<td>Unspecified</td>
<td>All types (All severities)</td>
<td>0.75</td>
<td>N/A*</td>
</tr>
<tr>
<td>Provide short four-lane section</td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
<td>N/A*</td>
</tr>
</tbody>
</table>

Base Condition: Two-lane rural road.

NOTE: * Standard error of AMF is unknown.
AMF for TWLTL Lanes

\[ \text{AMF}_{9r} = 1.0 - 0.7 \, P_{D} \times P_{LT/D} \]

Where:

\[ P_{dwy} = \text{Driveway-related crashes as a proportion of total crashes} \]

\[ P_{dwy} = \frac{(0.0047 \, DD + 0.0024 \, DD^2)}{(1.199 + 0.0047 \, DD + 0.0024 \, DD^2)} \]

\[ DD = \text{drive density (driveways/mi > 5/mile)} \]

\[ P_{LT/D} = \text{Left turn accidents susceptible to correction by a TWLTL as a proportion of driveway related crashes (estimated as 0.50)} \]

AMF for Roadside Quality

Roadside Design is based on Roadside Hazard Ratings that are dependent on the roadside environment

Ratings range from 1 to 7:

- 1 = forgiving roadside environment
- 7 = unforgiving roadside environment
AMF for Roadside Quality

• Roadside Design

10.6.8. Roadside Design

\[
AMF_{HR} = \frac{e^{-0.6869 + (0.0668 \times HR)}}{e^{-0.4865}}
\]

Where:

HR = Hazard Rating

Roadside Hazard Rating AMF’s

<table>
<thead>
<tr>
<th>Roadside Obstacles</th>
<th>Clear zone width (ft)</th>
<th>Roadside Slope</th>
<th>Hazard Rating</th>
<th>AMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>None within clear Zone None</td>
<td>30 or more</td>
<td>Flatter than 1:4</td>
<td>1</td>
<td>0.875</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>30 or more</td>
<td>1:4</td>
<td>1.5</td>
<td>0.905</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>20 to 30</td>
<td>1:4</td>
<td>2</td>
<td>0.935</td>
</tr>
<tr>
<td>None within clear Zone Rock cut or cliff with no barrier</td>
<td>20 to 30</td>
<td>1:3</td>
<td>2.5</td>
<td>0.967</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>10 to 20</td>
<td>1:4</td>
<td>2.5</td>
<td>0.967</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>10 to 20</td>
<td>1:3</td>
<td>3</td>
<td>1.000</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>10 to 20</td>
<td>1:2 or steeper</td>
<td>3.5</td>
<td>1.034</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>5 to 10</td>
<td>1:4</td>
<td>4</td>
<td>1.069</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>5 to 10</td>
<td>1:3</td>
<td>5</td>
<td>1.143</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>5 to 10</td>
<td>1:2 or steeper</td>
<td>5.5</td>
<td>1.182</td>
</tr>
<tr>
<td>None within clear Zone None</td>
<td>0 to 5</td>
<td>N/A</td>
<td>6</td>
<td>1.222</td>
</tr>
<tr>
<td>Barrier 5-6.5 ft fro edge of travel way</td>
<td>None</td>
<td>N/A</td>
<td>4</td>
<td>1.069</td>
</tr>
<tr>
<td>Barrier 0-5 ft from edge of travel way</td>
<td>None</td>
<td>N/A</td>
<td>5</td>
<td>1.143</td>
</tr>
<tr>
<td>Rock cut or cliff with no barrier</td>
<td>None</td>
<td>N/A</td>
<td>7</td>
<td>1.306</td>
</tr>
</tbody>
</table>
AMF for Lighting

\[ AMF_{1ir} = 1.0 - ((1.0 - 0.72 \ p_{ir} - 0.83 \ p_{nr}) \ p_{nr}) \]

Exhibit 10-20: Nighttime Accident Proportions for Unlighted Roadway Segments

<table>
<thead>
<tr>
<th>Roadway Type</th>
<th>Proportion of total nighttime accidents by severity level</th>
<th>Proportion of accidents that occur at night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total and Injury ( p_{ir} )</td>
<td>PDO ( p_{pnr} )</td>
</tr>
<tr>
<td>2U</td>
<td>0.382</td>
<td>0.618</td>
</tr>
</tbody>
</table>

NOTE: Based on HSIS data for Washington (2002-2006)

• These are default values for nighttime crash proportions; replace with local information if available

AMF for Lighting

Exhibit 13-66: Potential Crash Effects of Providing Highway Lighting

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Setting (Road type)</th>
<th>Traffic Volume</th>
<th>Accident type (Severity)</th>
<th>AMF</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide highway lighting</td>
<td>All settings (All types)</td>
<td>Unspecified</td>
<td>All types (Nighttime injury) ((6))</td>
<td>0.72</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All types (Nighttime Non-Injury) ((3))</td>
<td>0.83</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All types (Nighttime injury)((8))</td>
<td>0.71</td>
<td>N/A^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All types (Nighttime all severities)((2))</td>
<td>0.80</td>
<td>N/A^2</td>
</tr>
</tbody>
</table>

Base Condition: Absence of lighting.

NOTE: Based on U.S. studies; Harkey et al., 2008; and International studies: Evk and Vaa 2004

Bold text is used for the most reliable AMFs. These AMFs have a standard error of 0.1 or less.

^ Standard error of the AMF is unknown.
AMF for Automated Speed Enforcement (AMF$_{12r}$)

Use of video or photographic identification in conjunction with radar or lasers to detect speeding drivers:

$$AMF_{12r} = 0.93$$

Predicting Safety Performance of Rural 2-Lane Highways – Example:

<table>
<thead>
<tr>
<th>ADT = 5,500 ADT</th>
<th>N$_{BR}$ = 9.11 crashes/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length = 6.2 miles</td>
<td>AMF$_1$ = 1.172</td>
</tr>
<tr>
<td>Lane Width = 10 ft</td>
<td>AMF$_2$ = 1.18</td>
</tr>
<tr>
<td>Shoulder Width = 2 ft gravel</td>
<td>AMF$_3$ = 1.00</td>
</tr>
<tr>
<td>Grade = 0%</td>
<td>AMF$_4$ = 1.00</td>
</tr>
<tr>
<td>Driveway Density =</td>
<td>AMF$_5$ = 1.00</td>
</tr>
<tr>
<td>Centerline Rumble = no</td>
<td>AMF$_7$ = 1.00</td>
</tr>
<tr>
<td>Passing Lanes = no</td>
<td>AMF$_8$ = 1.00</td>
</tr>
<tr>
<td>TWLTL = no</td>
<td>AMF$_9$ = 1.00</td>
</tr>
<tr>
<td>Roadside Hazard = 3</td>
<td>AMF$_{10}$ = 1.00</td>
</tr>
<tr>
<td>Lighting = no</td>
<td>AMF$_{11}$ = 1.00</td>
</tr>
<tr>
<td>Automated Speed Enf = no</td>
<td>AMF$_{12}$ = 1.00</td>
</tr>
</tbody>
</table>

$$N_{RS} = N_{BR} \times (AMF_1 \times AMF_2 \times AMF_3 \ldots \times AMF_n)$$

$$= 9.11 \times 1.172 \times 1.18 \times 1.00 \times 1.00 \ldots = 12.06$$
Session 2 Review:

- It is impossible to assess the safety of a facility without comprehensive crash data (True / False)

Session 2 Review:

For a combined width of Lane + Shoulder = 15 feet:
- is a 4 ft shoulder + 11 ft lane safer than a 3 ft shoulder + 12 ft lane? (yes/no)
- Combined AMF for 12’ lanes and 3’ shoulders = 1.00 X 1.129 = ?
- Combined AMF for 11’ lanes and 4’ shoulders = 1.029 X 1.086 = ?
**Session 2 Learning Outcomes:**

- Described the Crash Prediction Equations (SPF) for Two-Lane Rural Highway Segments
- Described Accident Modification Factors (AMF’s) for Two-Lane Rural Highway Segments

Questions and Discussion
Session 3

Prediction of Safety Performance for Horizontal Curves and Countermeasures

IL Route 125 approaching Ashland, IL

Session 3 Learning Outcomes:

• Describe geometric design of horizontal curves
• Describe the Crash Prediction Equations (SPF) for Horizontal Curves
• Describe Accident Modification Factors (AMF’s) for geometric countermeasures to reduce horizontal curve crashes
AASHTO Horizontal Curve Design Model

\[ e + f = \frac{V^2}{15R} \]

Where:
- \( V \) = design speed (mph)
- \( R \) = radius of curve (ft)
- \( e \) = superelevation
- \( f \) = design side friction

**AASHTO Design Model Assumptions**
- Passenger car tracks curve as a point mass
- Passenger car operates at design speed through curve
- Curve design should avoid loss of control due to skidding (i.e., during cornering)

**Horizontal Curve Terminology**

\[ D_c = \frac{5730}{R} \]

**Symbols**
- \( \Delta \) = Intersection or central angle, degrees
- \( R \) = Radius of Curve, feet
- \( D \) = Degree of Curve
- \( L \) = Length of Curve, feet
- \( T \) = Tangent distance, feet
- \( E \) = External distance, feet
- \( M \) = Middle Ordinate, feet
- \( L_o \) = Long chord, feet
- \( \ell \) = Length of arc between any two points on curve, feet
- \( d \) = Central angle subtended by arc \( \ell \), degrees
- \( \alpha \) = Deflection angle for any arc length, degrees
- \( x \) = Distance along tangent from P.C. or P.T. to any point \( P \) on curve, feet
- \( y \) = Offset (normal) from tangent at distance \( x \) to any point \( P \) on curve, feet

**Horizontal Sightline Offset**
AASHTO Horizontal Curve Design Model

Discussion

What is this functional design model based on?

- Driver comfort

\[ e + f = \frac{V^2}{15R} \]

AASHTO design model assumptions for ‘f’

- Assumes operation on dry pavement at design speed
- Conservatively set to “provide ample margin of safety against skidding”
- Few changes over the years in ‘f’
AASHTO Superelevation Policy

\[ e + f = \frac{V^2}{15R} \]

- ‘e’ is assumed to counteract ‘f’ on a “one to one” basis
- design values for ‘e’ are set by policy, with maximum values (.06, .08, .10) associated with operation under icy conditions
- various methods for distribution of ‘e’ are allowed by AASHTO

…..If a designer properly determines the appropriate \( V \) (design speed) for a highway; and if \( R \) (curve radius) is determined based on providing driver comfort; and if \( f \) (‘side friction’) is well below that normally provided by the pavement/tire interface; and if \( e \) (superelevation) is properly provided per design policy, then why is it that....
Research confirms differences in actual operations versus AASHTO assumptions

- Drivers’ selected speed behavior does not match design assumptions
- Sharper curves (<80 km/h or 50 mph) are driven faster (drivers are more comfortable)

Assumed versus Actual Curve Operations

- Drivers ‘overshoot’ the curve (track a path sharper than the radius)
- Path is a spiral
- Path overshoot behavior is independent of speed

Source: Bonneson, NCHRP 439 and Glennon et al (FHWA)
Assumed versus Actual Curve Operations

-- Some Insights from the Research

AASHTO Design Model Assumptions
- Passenger car tracks the curve as a point mass
- Passenger car operates at design speed through curve
- Curve design should avoid loss of control due to skidding (i.e., during cornering)

Observed Behavior from Research
- Most drivers ‘overshoot’ the radius of curve as designed
- Drivers vary their speeds on approaches to and through the curve
- Some trucks overturn before skidding (at relatively low speeds)

Accident Modification Factors (AMFs)

- Account for difference between base and actual geometry
- Estimate effects of individual geometry elements on safety
- Can be greater or less than 1:
  - < 1.0 -- lower crash frequency
  - > 1.0 -- increased crash frequency

\[ 1 - AMF = CRF \]
Predicting Safety Performance of Horizontal Curves

• Accident Modification Factors (AMF’s)

AMF_{\text{curve}} = \frac{1.55 \cdot L_c + (80.2/R) - 0.012 \cdot S}{1.55 L_c}

Where:
- \( L_c \) = Length of Curve (mi)
- \( R \) = Radius of Curve (ft)
- \( S \) = 1 if spiral transition is present, 0 if not present
### AMF for Horizontal Curves: Example

For: \( L_c = 480 \text{ feet} = 0.091 \text{ miles} \)

- \( R = 350' \); no spiral transition
- central angle = 78.6 degrees

\[
AMF_{3r} = \frac{1.55 L_c + \left( \frac{80.2}{R} \right) - 0.012S}{1.55L_c}
\]

\[
= \frac{(1.55 \times 0.091) + \left( \frac{80.2}{350} \right) - 0.012 \times 0}{1.55 \times 0.091}
\]

\[
= 2.62
\]

### AMF for Horizontal Curves: Exercise

For: \( L_c = 874 \text{ feet} = 0.166 \text{ miles} \)

- \( R = 637' \) with spiral transition
- central angle = 78.6 degrees

\[
AMF_{3r} = \frac{1.55 L_c + \left( \frac{80.2}{R} \right) - 0.012S}{1.55L_c}
\]

\[
= \frac{(1.55 \times 0.166) + \left( \frac{80.2}{637} \right) - 0.012 \times 1}{1.55 \times 0.166}
\]

\[
= ?
\]
**AMF for Superelevation**

AMF<sub>4r</sub> is based on “Superelevation variance” or SV

- For SV less than 0.01: AMF<sub>4r</sub> = 1.00
- For 0.01 ≤ SV < 0.02: AMF<sub>4r</sub> = 1.00 + 6(SV-0.01)
- For SV ≥ 0.02: AMF<sub>4r</sub> = 1.06 + 3(SV-0.02)

**Example:** Design e = 4%, Actual e = 2%

SV = 0.04 – 0.02 = 0.02

AMF<sub>4r</sub> = 1.06 + 3(0.02-0.02) = 1.06 + 3(0.0) = 1.06

---

**Session 3 Learning Outcomes:**

- Described geometric design of horizontal curves
- Described the Crash Prediction Equations (SPF) for Horizontal Curves
- Described Accident Modification Factors (AMF’s) for geometric countermeasures to reduce horizontal curve crashes
Questions and Discussion
Session 3X Horizontal Curve Exercise

Session 3x Exercise Learning Outcomes:

- Apply Crash Prediction Calculation to a 2-Lane Rural Highway
- Apply Accident Modification Factor for a Horizontal Curve on that Highway
Exercise 3X: Part I

- Route 468 is a 2 lane rural highway. This route has been identified as having a crash rate much higher than the statewide average for a similar type of roadway. Thus, it has been selected for additional engineering studies to recommend improvements.
- The analysis segment length is 316 feet, with an ADT of 10,250 veh/day. The lane width is 11 feet, with no shoulders. The existing roadside hazard rating is 3, and the driveway density is 5 driveways per mile. There are no horizontal or vertical curves in this segment, nor are there two-way left turn lanes or passing lanes. Because we have no data on the crash types, assume the default distribution for correcting the AMF’s.

Exercise 3X: Part I

- Calculate the predicted safety performance, in crashes per year, for this highway segment.

\[ N_{BR} = (ADT) \times (L) \times (365) \times (10^{-6}) \times (0.7320) \]

\[ N_{BR} = (10,250) \times (316/5280) \times (365) \times (10^{-6}) \times (0.7320) \]

\[ N_{BR} = \text{? crashes per year} \]
**AMF for Lane Width**

This factor applies to single vehicle run-off-road, multi-vehicle (both same and opposite direction, sideswipe, and head-on) crashes to total crashes.

- \[ AMF_{\text{lane}} = 0.574 \]

**AMF - Adjustment for Related Crashes**

Adjust for (Run off Road + Head-on + Sideswipes) to total crashes:

- \[ AMF_{\text{related}} = (AMF_{\text{lane}} - 1.0) \cdot p_{ra} + 1.0 \]

With \( p_{ra} = 0.574 \)
AMF for Shoulder Width

AMF for Shoulder Width

AMF - Adjustment for Related Crashes

- Adjust for (Run off Road + Head-on + Sideswipes) to total crashes

\[
AMF_{Jr} = (AMF_{ra} - 1.0) p_{ra} + 1.0
\]

\[p_{ra} = 0.574\]
Predicted Crashes for Roadway Segment

\[ N_{RS} = N_{BR} \times (AMF_1 \times AMF_2 \times AMF_3 \ldots AMF_n) \]

Exercise 3x: Part II

• The segment described above is now a horizontal curve. The horizontal curve has a radius of 600 feet. There are no spirals present, but the super elevation meets AASHTO Green Book Policy.
### AMF for Horizontal Curves

\[
\text{AMF}_{\text{curve}} = \frac{1.55L_c + (80.2/R) - 0.012 * S}{1.55L_c}
\]

Where:
- \(L_c\) = Length of Curve (mi)
- \(R\) = Radius of Curve (ft)
- \(S\) = 1 if spiral transition is present, 0 if not present

### Predicted Crashes for Curve Segment

\[
N_{RS} = N_{BR} * (\text{AMF}_1 * \text{AMF}_2 * \text{AMF}_3 * \ldots \text{AMF}_n)
\]

\[
N_{RS} = \]

---

**Exercise 3X**

**Sept 2009**
Session 3x Exercise Learning Outcomes:

- Applied Crash Prediction Calculation to a 2-Lane Rural Highway
- Applied Accident Modification Factor for a Horizontal Curve on that Highway

Questions and Discussion
Session 3X: Exercise  
TWO-LANE RURAL Highway

Part I:  
From the Route 468 information, perform the following:

1. Predict the Crash Performance for the following:

   a. SPF Base Model for Route 468:

\[
N_{spf-rs} = (ADT_n) \times (L_{total}) \times (365) \times (10^{-6}) \times e^{-0.312}
\]

\[
= (\underline{\text{ADT}_n}) \times (\underline{L_{total}}) \times (365) \times (10^{-6}) \times e^{-0.312}
\]

\[
= \underline{\text{crashes per year}}
\]

b. SPF Base Model with AMF's for Lane Width, Shoulder Width, Hazard Rating, Access Density (Straight and Level)

\[
AMF_{ra} \text{ for Lane Width from Exhibit 10-14: }
\]

\[
AMF_{1r} = (AMF_{ra} - 1.0) p_{ra} + 1.0
\]

\[
AMF_{wra} \text{ for Shoulder Width from Exhibit 10-16: }
\]

\[
AMF_{tra} \text{ for Shoulder Type from Exhibit 10-18: }
\]

\[
AMF_{2r} = (AMF_{wra} \times AMF_{tra} - 1.0) p_{ra} + 1.0
\]

\[
N_{predicted-rs} = N_{spf-rs} \times AMF_{1r} \times AMF_{2r}
\]

\[
= \underline{\text{N}_{spf-rs}} \times \underline{\text{AMF}_{1r}} \times \underline{\text{AMF}_{2r}}
\]

\[
= \underline{\text{crashes per year}}
\]
Part II:
From the Route 468 information for a horizontal curve of length = 316/5280, with radius of 600 feet and no spiral transition with super elevation in conformance with the AASHTO Policy on Geometric Design, perform the following:

2. Compute the Weighted AMF for the horizontal curve
   
   b. \( \text{AMF}_{\text{curve}} = \frac{1.55 \ L_c + (80.2/R) - 0.012 \ Is}{1.55L_c} \)

   \( = (1.55 \ \text{ } + \frac{80.2}{\text{ }} ) - 0.012 \ \text{ } \)

   \( / 1.55 \)

   \( = \)

   c. Compute the prediction of crashes for the Horizontal Curve

   \( N_{\text{curve}} = N_{\text{predicted}} \times \text{AMF}_{\text{curve}} \)

   \( = \ \text{ } \times \ \text{ } \)

   \( = \text{crashes per year} \)
Session 4

Measures to Reduce Horizontal Curve Crashes – NCHRP 500 Volume 7

Session 4 Learning Outcomes:

• Describe measures to reduce horizontal curve crashes identified in NCHRP 500 volume 7
15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve.

AASHTO Design Values for Lane and Shoulder Widths on 2-Lane highways

<table>
<thead>
<tr>
<th>Metric</th>
<th>US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum width of traveled way (ft) for specified design volume (veh/day)</td>
</tr>
<tr>
<td></td>
<td>Design speed (mph)</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>130</td>
</tr>
</tbody>
</table>

On roadways to be reconstructed, an existing 6.6 m [22-ft] traveled way may be retained where alignment and safety records are satisfactory.

Usable shoulders on arterials should be paved; however, where volumes are low or a narrow section is needed to reduce construction impacts, the paved shoulder may be reduced to 0.6 m [2 ft].

Exhibit 7-3. Minimum Width of Traveled Way and Usable Shoulder for Rural Arterials

Substantive Safety

Improving Safety of Horizontal Curves
Countermeasures to Reduce Crashes for Horizontal Curves

Widening on Inside of Curve

Widening on Outside of Curve
Countermeasures to Reduce Crashes
for Horizontal Curves

15.2 A11 Widen the roadway

Important Conclusions from NCHRP Report 362

- Lane and shoulder width influence other operational factors (capacity, maintenance, other users)
- Cross section and alignment should be consistent (i.e., should produce consistent and appropriate speed behavior)

For lower traffic volumes the costs of wider cross section values are not justified
- 9- and 10-foot lanes are appropriate for very low volume roads

AASHTO design values for two-lane rural lane and shoulder widths are based on NCHRP Report 362
- Reflect safety cost-effectiveness
- Include operations (speed and LOS)
15.2 A11 Widen the roadway

Operational Effects of Width

- Wider Lane Widths
- Greater Capacity
- Increased Speeds

- Wider Shoulder Widths
- Greater Capacity
- Increased “Functionality”
- Increased Speeds

Overview of Research on Shoulder Widths (Hauer)

- Paved shoulders offer safety benefits over unpaved shoulders
- Wider shoulders are associated with fewer run-off-road and opposite direction crashes; but may be associated with more of other types of crashes
Conclusions Regarding Safety Effects of Lane and Shoulder Width

- Total cross section is important (lane and shoulder width, roadside)
- There is little or no safety effectiveness in widening lanes from 11 to 12 feet
- Shoulders serve as clear zones (run-off-road crashes)
- Lane width contributes to speed behavior; consistency with alignment is important

Key Findings of FHWA Cross Section Study (Zegeer)

- Traffic volume influences crash rate
- Both lane and shoulder width have influence
- Roadside Hazard strongly influences crashes
- Alignment affects cross section crashes (terrain is surrogate for alignment)
15.2 A11 Widen the roadway

For 4,000 ADT and a 14 foot wide lane with edgeline 2 feet “in” + 6 foot aggregate shoulder, what is Total AMF?

- Lane Width = 12’ AMF$_{1r}$ = 1.0;
- Shoulder Width = 2’ + 6’ = 8’ AMF$_{wra}$ = 0.87
- Combination Shoulder AMF$_{tra}$ = (2’/8’)$ \times $1.00 + (6’/8’) $ \times $ 1.02 = 1.015

AMF$_{2r}$ = (AMF$_{wra}$ AMF$_{tra}$ - 1.0) $p_{ra}$ + 1.0

AMF$_{2r}$ = ((0.87x1.015)-1.0)(0.574) + 1.0 = 0.933

Total AMF$_{1r&2r}$ = 1.0 x 0.933 = 0.933
Examples of Improving Safety of Existing Curves

- Widen 3’ Shoulder to 6’ Shoulder
  NY Rte 82 north of Millbrook

15.2 A11 Widen the roadway
15.2 A11 Widen the roadway

Section 2C.31 Shoulder Signs (W8-4, W8-9, and W8-9a) (2009 MUTCD)

Option:
- The SOFT SHOULDER (W8-4) sign (see Figure 2C-6) may be used to warn of a soft shoulder condition.
- The LOW SHOULDER (W8-9) sign (see Figure 2C-6) may be used to warn of a shoulder condition where there is an elevation difference of less than 3 inches between the shoulder and the travel lane.
- The NO SHOULDER (W8-23) sign (see Figure 2C-6) may be used to warn road users that a shoulder does not exist along a portion of the roadway.
- The SHOULDER ENDS (W8-25) sign (see Figure 2C-6) may be used to warn road users that a shoulder is ending.
Section 2C.31 Shoulder Signs (2009 MUTCD)

Guidance:
- The Shoulder Drop Off (W8-17) sign (see Figure 2C-6) should be used where an unprotected shoulder drop-off, adjacent to the travel lane, exceeds 3 inches in depth for a significant continuous length along the roadway, based on engineering judgment.

Option:
- A SHOULDER DROP-OFF (W8-17P) supplemental plaque (see Figure 2C-6) may be mounted below the W8-17 sign.

Section 6F.42 Shoulder Signs (W8-4, W8-9, W8-9a)

Drop-offs or edge rutting was present in 56% of the fatal crashes studied on 2 lane rural roads in one state.

Another state found drop-offs or edge rutting was present in 47% of their cases.


15.2 A11 Widen the roadway

Section 6F.42 Shoulder Signs (W8-4, W8-9, W8-9a)

According to the National Transportation Safety Board, the most lawsuits filed against highway authorities are for shoulder drop off related crashes.

NTSB - 10-20% of fixed object crashes are repeats at the same locations as previous crashes.

15.2 A3 Provide adequate sight distance

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve.
15.2 A3 Provide adequate sight distance

"Nominal Safety"

Stopping sight distance is the sum of (1) the distance traversed by the vehicle from the instant the driver sees an object necessitating a stop to the instant the brakes are applied (i.e., the brake reaction distance) and (2) the distance needed to stop the vehicle from the instant the brakes are applied (i.e., the braking distance).

\[ SSD = 1.47 \frac{Vt}{a} + 1.075 \frac{V^2}{a} \]
15.2 A3 Provide adequate sight distance

Table: Stopping Sight Distance

<table>
<thead>
<tr>
<th>Vehicle Speed (mph)</th>
<th>Reaction Distance (feet)</th>
<th>Braking Distance (feet)</th>
<th>Summed Distance (feet)</th>
<th>Stopping Sight Distance (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>55.1</td>
<td>21.6</td>
<td>76.7</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td>73.5</td>
<td>38.4</td>
<td>111.9</td>
<td>115</td>
</tr>
<tr>
<td>25</td>
<td>91.9</td>
<td>60.0</td>
<td>151.9</td>
<td>155</td>
</tr>
<tr>
<td>30</td>
<td>110.3</td>
<td>86.0</td>
<td>196.7</td>
<td>200</td>
</tr>
<tr>
<td>35</td>
<td>128.6</td>
<td>117.6</td>
<td>246.2</td>
<td>230</td>
</tr>
<tr>
<td>40</td>
<td>147.0</td>
<td>153.5</td>
<td>300.5</td>
<td>305</td>
</tr>
<tr>
<td>45</td>
<td>165.4</td>
<td>194.4</td>
<td>359.8</td>
<td>380</td>
</tr>
<tr>
<td>50</td>
<td>183.8</td>
<td>240.0</td>
<td>423.8</td>
<td>425</td>
</tr>
<tr>
<td>55</td>
<td>202.1</td>
<td>290.3</td>
<td>492.4</td>
<td>495</td>
</tr>
</tbody>
</table>

*Exhibit 3-1. Stopping Sight Distance (1) Distances are for dry conditions and may change in future versions.*

A driver needs an adequate view of the roadway alignment and roadway features ahead for safe control and guidance of the vehicle (Gattis and Duncan, 1995). This sight distance to the roadway surface and other appurtenances ahead is referred to as preview sight distance (PVSD).

**Good PVSD**

**Poor PVSD**
15.2 A3 Provide adequate sight distance

Primary Considerations When Addressing Horizontal Curve Sight Distance.

- Does the curve meet "Nominal Safety."
- Is there a "Substantive Safety" problem caused by limited sight distance.

Improving Safety of Horizontal Curves
Maintenance – Sight Distance

Maintenance – Sight Distance
Maintenance – Sight Distance

Sight Distance Before
Countermeasures to Reduce Crashes for Horizontal Curves

Sight Distance After

15.2 A12 Improve or restore superelevation

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve
Many curves may have inadequate superelevation due to:
- Vehicles traveling at higher speeds than were originally designed for;
- Loss of effective superelevation after resurfacing;
- Changes in design policy after the curve was originally constructed.

Research results indicate that safety can be enhanced when the superelevation is improved or restored along curves where the actual superelevation is less than the optimal superelevation. (Zegeer et al., 1992)
Superelevation deficiency is the numerical difference between the optimal superelevation (as determined from AASHTO policy) and the actual superelevation of a given curve.

**AMF for Superelevation**

AMF<sub>4r</sub> is based on “Superelevation variance” or SV

- For SV less than 0.01:  AMF<sub>4r</sub> = 1.00
- For 0.01 ≤ SV < 0.02:  AMF<sub>4r</sub> = 1.00 + 6(SV-0.01)
- For SV ≥ 0.02:  AMF<sub>4r</sub> = 1.06 + 3(SV-0.02)

**Example:** Design e = 4%, Actual e = 2%

SV = 0.04 − 0.02 = 0.02

AMF<sub>4r</sub> = 1.06 + 3(0.02-0.02) = 1.06 + 3(0.0) = 1.06
Considerations When Addressing Superelevation deficiencies.

- It is important to limit the slope break between the elevated edge of pavement and the adjacent shoulder.
- Ensure the proper transition from the normal cross slope along the tangent to the fully superelevated cross slope along the curve.
- Finally, care should be given to provide proper drainage when improving or restoring the superelevation along a curve.

15.2 A12 Improve or restore superelevation
15.2 A13 Modify horizontal alignment

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve

Both ROR and head-on crashes are 1.5 to 4 times more likely to occur on curves than on tangents (Glennon et al., 1985).
Strategy 15.1 A5 — Improved Highway Geometry for Horizontal Curves

<table>
<thead>
<tr>
<th>Original Degree of Curve</th>
<th>New Degree of Curve</th>
<th>Percent Reduction in Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>25</td>
<td>15 - 17</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>31 - 32</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>40 - 50</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>61 - 67</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>79 - 83</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>17 - 22</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>55 - 62</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>55 - 80</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>72 - 80</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>20 - 25</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>41 - 50</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>64 - 75</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>24 - 32</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>50 - 60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>68 - 79</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>29 - 49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>42 - 60</td>
</tr>
</tbody>
</table>

Crash Reduction Factors
Curve Geometry from Glennon Data

Greatest reductions in crashes are expected for smallest central angles and sharpest original curvature

Source: TRB Special Report 214
Countermeasures to Reduce Crashes for Horizontal Curves

15.2 A13
Modify horizontal alignment (add spiral transitions)
Session 4 Review:

- Spiral Transitions are inconsistent with the way people drive through curves (True / False)

Session 4 Learning Outcomes:

- Described measures to reduce horizontal curve crashes identified in NCHRP 500 volume 7
Questions and Discussion
Session 5

Pavement Countermeasures for Reducing Roadway Departure Crashes

Session 5 Learning Outcomes:

• Identify pavement countermeasures for reducing roadway departure crashes
15.2 A6 - Prevent edge drop-offs

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve.

Many highway agencies leave an “abrupt” edge when resurfacing.
15.2 A6 - Prevent edge drop-offs

County Road recently resurfaced – Edge drop-off resulted in 3 Fatalities

Vehicle Re-entry
Safety Edge

FHWA/ GDOT has a demonstration project in Georgia to show the construction feasibility of implementing the “Safety Edge”

Line depicts a plane parallel to Pavement Surface from the toe of the wedge surface

30° - 35°
Improving Safety of Horizontal Curves
Georgia DOT Shoe

Version V

5-13

5-14
TransTech Shoulder Wedge Maker
Increased Edge Compaction

With Safety Edge  |  Without Safety Edge

Condition After One Year In-Service

With Safety Edge  |  Without Safety Edge
15.2 A6 - Prevent edge drop-offs

After shoulder has been pulled back on Safety Edge

![Graph showing relative degree of safety vs. longitudinal edge elevation change](image)
Benefits of A Safety Edge

- Immediate and long term mitigation to drop-offs
- Reduce tort liability
- Cost less than 1% of material costs
- Increased pavement edged durability

15.2 A4 Install shoulder rumble strips

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve
15.2 A4 Install shoulder rumble strips

Divided Highways

Edgeline Rumble Strip on 2-Lane Rural Highway

(bicycle friendly with gaps)
Safety Effects of Installing Shoulder Rumble Strips- 2 Lane Highways

The Draft Highway Safety Manual does not have an AMF for Shoulder Rumble Strips

\[ AMF_{\text{rumble}} = 0.85 \]

* Draft NCHRP study results

15.2 A4 Install shoulder rumble strips
15.2 A4 Install shoulder rumble strips

Rumble Stripes – a Pavement Marking Innovation

- Mississippi evaluated several different sized rumble strips and striping patterns over a 20 mile stretch of I-59 around Hattiesburg.
- 6”, 9”, 12”, and the standard 16” rumble strips were installed with the edge stripe located in the rumble strip.
15.2 A4 Install shoulder rumble strips

Mississippi

6-inch “Rumble Stripes”

15.2 A4 Install shoulder rumble strips

Mississippi

12-inch “Rumble Stripes”
15.2 A4 Install shoulder rumble strips

Mississippi

16-inch “Rumble Stripes”

Rumble Stripes on MS 589

Mississippi
15.2 A4 Install shoulder rumble strips

Rumble Stripes on MS 589

Mississippi

Rumble Stripes

Michigan initiative with edge line painted over shoulder rumble strip.

Normal Edgeline

Comparison of painted edgeline in Rain
15.2 A4 Install shoulder rumble strips

Michigan initiative with edge line painted over shoulder rumble strip.

Michigan I-75 - After 1st Winter

15.2 A5 Install centerline rumble strips

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve
15.2 A5 Install centerline rumble strips

Centerline Rumble Strip

15.2 A5 Install centerline rumble strips

Centerline Rumble Strip
15.2 A5 Install centerline rumble strips

Highway Safety Manual

Exhibit 13-55: Potential Crash Effects of Installing Centerline Rumble Strips

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Setting (Road type)</th>
<th>Traffic Volume AADT</th>
<th>Accident type (Severity)</th>
<th>AMF</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Install centerline rumble strips</td>
<td>Rural (Two-lane)</td>
<td>5,000 to 22,000</td>
<td>All types (All severities)</td>
<td>0.86</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All types (Injury)</td>
<td>0.85</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Frontal and opposing direction sidewipe (All severities)</td>
<td>0.79</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Frontal and opposing direction sidewipe (Injury)</td>
<td>0.75</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Base Condition: Absence of centerline rumble strips.

NOTE: Based on centerline rumble strip installation in seven states: California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington.

5-39

15.2 A5 Install centerline rumble strips

Table 2

<table>
<thead>
<tr>
<th>Miles</th>
<th>Site</th>
<th>Crash Type</th>
<th>Crashers Recorded in After Period</th>
<th>Empirical Bayes Estimate of Crashes Expected After without Centerline Rumble Strips (Standard Error)</th>
<th>Percent Reduction (95% Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150.8</td>
<td>90</td>
<td>All</td>
<td>1.491 (52)</td>
<td>1.724 (39.8) 629.1 (22.7)</td>
<td>14% (9-20%) 15% (5-25%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frontal/opposing-direction sidewipe</td>
<td>147 (81)</td>
<td>185.5 (10.5) 106.7 (7.7)</td>
<td>21% (5-37%) 25% (5-44%)</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Miles</th>
<th>Site</th>
<th>Time of Day</th>
<th>Crashers Recorded in After Period</th>
<th>Empirical Bayes Estimate of Crashes Expected After without Centerline Rumble Strips (Standard Error)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>150.8</td>
<td>90</td>
<td>Day</td>
<td>840</td>
<td>9.31.1 (20.7)</td>
<td>9% (p&lt;0.005)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Night</td>
<td>630</td>
<td>7.41.2 (24.6)</td>
<td>19% (p&lt;0.001)</td>
</tr>
</tbody>
</table>

Results for individual states are shown in Table 4. Numbers were sparse for many of the comparisons, especially for those limited to opposing-direction crashes. However, results generally were consistent across the states, with all showing reductions in all crashes combined. In one state, Minnesota, there was an estimated increase in opposing-direction injury crashes, but this was not statistically significant.

5-40
15.2 A5 Install centerline rumble strips

15.2 A5 Install centerline rumble strips
15.2 A7 Provide skid-resistant pavement surfaces

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve

• Between 1995 and 1997, 36 sites were treated on Long Island, resulting in a reduction of more than 800 annually recurring wet-road accidents.
• Results support earlier findings that improving the skid resistance at locations with high wet-road accident frequencies results in reductions of;
  • 50 percent for wet-road accidents; and
  • 20 percent for total accidents.
15.2 A7 Provide skid-resistant pavement surfaces

The margin of safety against skidding on curves is defined as the difference between the available tire-pavement friction and the friction demand of the vehicle as it tracks the curve.

Strategy 15.2 A7: Provide Skid-Resistant Pavement Surfaces (T)

General Description

Current design criteria for horizontal curves are formulated to provide comfort to the driver in tracking the curve while keeping vehicles from skidding on wet pavements. The criteria
15.2 A7 Provide skid-resistant pavement surfaces

The likelihood of skidding increases when these assumed conditions are violated. Several studies have shown that under real-world conditions both of these assumptions are violated to some degree (Bonneson, 2000; Glennon et al., 1985; Glennon and Weaver, 1972), with the result being that at many curve sites the assumed margin of safety may actually be overestimated. Where this is the case and there is evidence of loss of control because of skidding, several solutions are evident. Solutions may include modifications to the alignment and

AASHTO Horizontal Curve Design Model

\[ e + f = \frac{V^2}{15} R \]

- \( e \) = superelevation
- \( f \) = side friction factor
- \( V \) = design speed (mph)
- \( R \) = radius of curve (ft)
Basis for Curve Design Model Is *Driver Comfort*

Although the curve design policy stems from the laws of mechanics, the values used in design depend on practical limits and factors determined empirically over the range of variables involved.

**Speeds on Curves - Driver Behavior Vs. Model Assumptions**

Curves driven faster than Policy assumption
Curves driven slower than Policy assumption
Truck Operations on Curves

- Trucks with high centers of gravity may overturn before losing control due to skidding.
- Trucks on downgrade curves generate greater lateral friction (Superelevation Is Not As Effective).
- Margin of safety for ‘f’ is lower for trucks.

Technical Advisory T 5040.36 - Surface Texture for Asphalt and Concrete Pavements

U.S. Department of Transportation
Federal Highway Administration

Technical Advisory
Subject: Surface Texture for Asphalt and Concrete Pavements

<table>
<thead>
<tr>
<th>Classification Code</th>
<th>Date</th>
<th>Office of Primary Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 5040.36</td>
<td>June 17, 2005</td>
<td>HIPT-20</td>
</tr>
</tbody>
</table>
Royal Palms I-75 entrance ramp Tyregrip installed to reduce the amount of off road skidding accidents.
Installation of a Microtexture surface on a dangerous negative cambered curve for the City of Bellevue, Washington. Prior to the installation, this location had 45 accidents.

15.2 A7 Provide skid-resistant pavement surfaces

Installation by hand
First lane side completed
After 24 months
15.2 A7 Provide skid-resistant pavement surfaces

Rural route Hamilton County OH reduced Run off the road accidents.
Improving Safety of Horizontal Curves

- #2 on PennDot safety projects list
- Sharp right turn with vehicles skidding into NB lane during wet conditions
- 2.48 crash rate includes head on, side swipe, hit fixed object
- 3 deaths, 4 injury crashes, and 20 total crashes in 8 years
- Avg. surface skid resistance before 33

Braking Video

Stopping distances on wet pavements.
15.2 A7 Provide skid-resistant pavement surfaces

Some states, including California, resurface short roadway segments such as horizontal curves with open-graded asphalt friction courses to improve skid resistance and safety.
Friction Testing

Improving Skid Resistance
15.2 A8 Provide grooved pavement

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve.

Pavement grooving is a way to add texture to the pavement surface, but its primary objective is to improve the drainage and to mitigate hydroplaning. The grooves decrease the water film thickness on a pavement surface and allow for greater tire-pavement surface interaction during adverse weather conditions.
15.2 A8 Provide grooved pavement

Safety Effectiveness of Pavement Grooving

Numerous studies on the safety effectiveness of pavement grooving have been conducted, but none of these studied have controlled for regression to the mean so the results should be considered with caution.

Wong (1990) performed a before-after evaluation of the effectiveness of pavement grooving from one site in California. Two-lane highway with steep vertical grades and sharp horizontal curves. Based upon data from a 3-year before period and a 1-year after period:
- 72-percent reduction in wet-pavement accidents, while only finding a reduction of about 7 percent in dry-pavement accidents.
NYDOT evaluated the safety effectiveness of pavement grooving at 41 sites.

- Wet-road accidents were reduced by 55 percent; and
- total accidents (dry and wet) were reduced by 23 percent.
- The results were statistically significant at the 95th percentile. Regression to the mean was not addressed in the analysis.

Safety Effectiveness of Pavement Grooving

- Grooves cut in the longitudinal direction have proven most effective in increasing directional control of the vehicle,
- Transverse grooving is most effective where vehicles make frequent stops, such as intersections, crosswalks, and toll booths. When pavements are grooved, it is important that the pavement contain nonpolishing aggregate.
15.2 A8 Provide grooved pavement

Safety Effectiveness of Pavement Grooving
– Consider noise
– Impact on certain road users, including

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Roadside Data Rankings (dBA)</th>
<th>Onboard Data Rankings (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Left Channel</td>
</tr>
<tr>
<td>Novaclot (aged)</td>
<td>79.5</td>
<td>79.8</td>
</tr>
<tr>
<td>Microsurfacing (Mapac @ 45th)</td>
<td>80.1</td>
<td>80.9</td>
</tr>
<tr>
<td>Course Matrix High Binder</td>
<td>80.7</td>
<td>80.6</td>
</tr>
<tr>
<td>Asphalt (new)</td>
<td>81.5</td>
<td>81.6</td>
</tr>
<tr>
<td>Novaclot (new)</td>
<td>81.6</td>
<td>82.0</td>
</tr>
<tr>
<td>JRC (ungrooved)</td>
<td>81.9</td>
<td>81.8</td>
</tr>
<tr>
<td>CRC (united)</td>
<td>82.4</td>
<td>82.0</td>
</tr>
<tr>
<td>Microsurfacing (Corpus Christi)</td>
<td>82.5</td>
<td>82.6</td>
</tr>
<tr>
<td>Asphalt (aged, Mapac @ 45th)</td>
<td>83.1</td>
<td>82.9</td>
</tr>
<tr>
<td>CRC (treated, aged)</td>
<td>83.8</td>
<td>84.0</td>
</tr>
<tr>
<td>CRC (treated, new)</td>
<td>83.9</td>
<td>83.8</td>
</tr>
<tr>
<td>Chip Seal (Grade 4)</td>
<td>84.4</td>
<td>84.5</td>
</tr>
<tr>
<td>Asphalt (aged, Decker Lane)</td>
<td>84.4</td>
<td>84.4</td>
</tr>
<tr>
<td>JRC (grooved)</td>
<td>84.8</td>
<td>85.1</td>
</tr>
<tr>
<td>Asphalt (grooved)</td>
<td>86.0</td>
<td>86.3</td>
</tr>
</tbody>
</table>

“Comparative Field Measurements of Tire Pavement Noise of Selected Texas Pavements”
Grooved Pavements

Session 5 Review:

• A low cost treatment for pavement edge drop-offs is the_________________.

5-99

5-100
Session 5 Review:

- Rumble strips are only effective on freeways (True / False)

Session 5 Review:

The basis for the AASHTO curve design is safety (True / False)
Session 5 Learning Outcomes:

• Identified pavement countermeasures for reducing roadway departure crashes

Questions and Discussion
Session 6

Signing and Marking of Horizontal Curves

Session 6 Learning Outcomes:

• Describe Requirements for Warning Signs for Horizontal Curves
• Describe Pavement Markings for Horizontal Curves
2003 and Earlier MUTCD’s

Section 2C.02 Application of Warning Signs
Standard:
The use of warning signs shall be based on an engineering study or on engineering judgment.

Section 2C.06 Horizontal Alignment Signs (W1-1 through W1-5, W1-11, W1-15)
Option:
The horizontal alignment Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), or Winding Road (W1-5) signs (see Figure 2C-1) may be used in advance of situations where the horizontal roadway alignment changes. A One-Direction Large Arrow (W1-6) sign (see Figure 2C-1 and Section 2C.09) may be used on the outside of the turn or curve. If the change in horizontal alignment is 135 degrees or more, the Hairpin Curve (W1-11) sign (see Figure 2C-1) may be used. If the change in horizontal alignment is approximately 270 degrees, such as on a cloverleaf interchange ramp, the 270-degree Loop (W1-15) sign (see Figure 2C-1) may be used.

Result = 25% of all Fatal Crashes on Horizontal Curves

2009 MUTCD

Recommended and Required Warning Signs based upon Highway Safety Manual

Section 2C.02 Application of Warning Signs
Standard:
The use of warning signs shall be based on engineering study or on engineering judgment.

Section 2C.06 Horizontal Alignment Warning Signs
Standard:
In advance of horizontal curves on freeways, on expressways, and on roadways with more than 1,000 AADT that are functionally classified as arterials or collectors, horizontal alignment warning signs shall be used in accordance with Table 2C-5 based on the speed differential between the roadway’s posted or statutory speed limit or 85th-percentile speed, whichever is higher, or the prevailing speed on the approach to the curve, and the horizontal curve’s advisory speed.
New Curve Warning Signs – 2009 MUTCD

Enhanced Figure 2C-2 – 2009 MUTCD
Support: Among the established engineering practices that are appropriate for the determination of the recommended advisory speed for a horizontal curve are the following:

A. An accelerometer that provides a direct determination of side friction factors
B. A design speed equation
C. A traditional ball-bank indicator using the following criteria:

- 16 degrees of ball-bank for speeds of 20 mph or less
- 14 degrees of ball-bank for speeds of 25 to 30 mph
- 12 degrees of ball-bank for speeds of 35 mph and higher
Support:

The 16, 14, and 12 degrees of ball-bank criteria are comparable to the current AASHTO horizontal curve design guidance. Research has shown that drivers often exceed existing posted advisory curve speeds by 7 to 10 mph.

See the “Guidelines for Determination of Advisory Speeds” by Robert Seyfried and Jim Pline to be published in ITE Journal (attached).
Enhanced Warning Signing for Curves

Chevron Horizontal Alignment Signs:

CRF = 35%

Tried

2009 MUTCD Chapter 2C:

Table 2C-5. Horizontal Alignment Sign Selection

<table>
<thead>
<tr>
<th>Type of Horizontal Alignment Sign</th>
<th>Difference Between Speed Limit and Advisory Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mph</td>
</tr>
<tr>
<td>Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10-1) (see Section 2C.07 to determine which sign to use)</td>
<td>Recommended</td>
</tr>
<tr>
<td>Advisory Speed Zone (L10-8)</td>
<td>Recommended</td>
</tr>
<tr>
<td>Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)</td>
<td>Optional</td>
</tr>
<tr>
<td>Exit Speed (W1-12), Winding Speed (W13-3) on exit ramp</td>
<td>Optional</td>
</tr>
</tbody>
</table>

*Chevrons are now required where the Curve Differential Speed is 15mph or more
Signing a Curve – Missouri Example

Chevron signs, when used, are erected on the outside of a curve, sharp turn, or on the far side of an intersection, in line with and at right angles to the approaching traffic.

Spacing of the signs should be such that the motorist always has two Chevrons in view, until the change in alignment eliminates the need for the signs.

Missouri Example: 4 degree curve with 1,200 foot radius

Chevron Alignment Warning

Signing a Curve – Missouri Example

PT
PC

Speed Limit = 55 mph
Advisory Speed = 45 mph
SuperElevation = 0 degrees
Radius = 5 degree, 1,000 ft


### Signing and Marking for Horizontal Curves

#### 2009 MUTCD Chapter 2C:

**Table 2C-5. Horizontal Alignment Sign Selection**

<table>
<thead>
<tr>
<th>Type of Horizontal Alignment Sign</th>
<th>Difference Between Speed Limit and Advisory Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mph</td>
</tr>
<tr>
<td>Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10) (see Section 2C.07 to determine which sign to use)</td>
<td>Recommended</td>
</tr>
<tr>
<td>Advisory Speed Plaque (W13-1P)</td>
<td>Recommended</td>
</tr>
<tr>
<td>Chevrons (W1-6) and One Direction Large Arrow (W1-6)</td>
<td>Optional</td>
</tr>
<tr>
<td>Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp</td>
<td>Optional</td>
</tr>
</tbody>
</table>

---

**Chevron Alignment Warning**

**Signing for Curves**

**Signing a Curve**

- Missouri Example

  - PT
  - PC

  Speed Limit = 55 mph
  Advisory Speed = 45 mph
  SuperElevation = 0 degrees
  Radius = 5 degree, 1,000 ft

  - What’s missing?

  > The required 45mph W13-1 Advisory Speed Plaque
2009 MUTCD Chapter 2C:

- For a differential speed of Speed Limit of 55 mph minus the Advisory Speed of 45 mph = 10 mph and radius of 1,000 feet

Table 2C-6. Typical Spacing of Chevron Alignment Signs on Horizontal Curves

<table>
<thead>
<tr>
<th>Advisory Speed</th>
<th>Curve Radius</th>
<th>Sign Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 or less</td>
<td>Less than 200</td>
<td>40</td>
</tr>
<tr>
<td>20 to 30</td>
<td>200 to 400</td>
<td>60</td>
</tr>
<tr>
<td>35 to 45</td>
<td>401 to 700</td>
<td>120</td>
</tr>
<tr>
<td>50 to 60</td>
<td>701 to 1,250</td>
<td>160</td>
</tr>
<tr>
<td>More than 60</td>
<td>More than 1,250</td>
<td>200</td>
</tr>
</tbody>
</table>

Note: The relationship between the curve radius and the advisory speed shown in this table should not be used to determine the advisory speed.

- Table 2C-6 is “Guidance” and based upon engineering judgment
- “Should” Use 120 feet to 160 feet based upon advisory speed and radius

Advance Warning Signing for Curves

CRF = 30%

Tried
Enhancing Warning Signing for Curves

**Oversize**

![Image of warning sign for oversize vehicles]

Enhancing Warning Signing for Curves

**Oversize Background**

![Image of another warning sign for oversize vehicles]

6-19

6-20
Enhancing Warning Signing for Curves

**Doubled-Up**

- Put a standard warning sign on a larger background

Enhancing Warning Signing for Curves

- Put a standard warning sign on a larger background
Enhancing Warning Signing for Curves

Yellow Warning Flashers

Enhancing Warning Signing for Curves

Yellow Warning Flashers
Enhancing Warning Signing for Curves

Dynamic CMS Signs

US 2 south of Glacier National Park
ADT = 5,500
Crashes = 5/yr

What Signing Safety Countermeasure would you apply?
Signing for Horizontal Curves: Exercise

Delineation and Markings for Curves

Delineation

CRF = 25%
Centerline and Edgeline Markings

Centerline with No-Passing Zones
CRF = 33% All Crashes

Edge lines
CRF = 44% All Crashes

Session 6 Review:

• A low cost measure to reduce crashes for Horizontal Curves is application of Advance Warning Signs; what is the expected crash reduction? ________________.
Session 6 Learning Outcomes:

- Described Requirements for Warning Signs for Horizontal Curves
- Described Pavement Markings for Horizontal Curves

Questions and Discussion
GUIDELINES FOR THE DETERMINATION OF ADVISORY SPEEDS

Robert K. Seyfried, PE, PTOE
and
James L. Pline, PE, PTOE

12/10/2008

Introduction
The determination and posting of advisory speeds for changes in horizontal alignment is a universal practice throughout the nation. It was initially tried by the State of Missouri in 1937 followed shortly thereafter by a number of other state highway departments. The pre-eminent research was done by R. A. Moyer and D. S. Berry (1) published by the Highway Research Board in 1940 as a recommendation for signing changes in roadway alignment. Curve advisory speed posting was adopted as a suggested option in the 1948 Manual on Uniform Traffic Control Devices (2).

The initial research by Moyer and Berry established the basic need, procedures and criteria for determining advisory speeds. The use of a ball-bank Indicator was recommended as an acceptable instrument for establishing a “safe speed” on a horizontal curve. Their recommendations were the following ranges of values:

Table 1. Recommended Criteria for Curve Advisory Speed Determination
(Source: Moyer and Berry, 1940, Ref. 1)

<table>
<thead>
<tr>
<th>Speeds (mph)</th>
<th>Ball Bank Reading</th>
<th>Side Friction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 20</td>
<td>14°</td>
<td>0.21</td>
</tr>
<tr>
<td>25 – 30</td>
<td>12°</td>
<td>0.18</td>
</tr>
<tr>
<td>≥ 35</td>
<td>10°</td>
<td>0.15</td>
</tr>
</tbody>
</table>
The Moyer/Berry research also indicated that the curve “safe speed” could be computed using the standard curve formula if the curve radii and superelevation were known using the above noted equivalent side friction factors. While they noted the advisory speed as being the “safe speed” for the curve, the advisory speed actually represented the comfortable speed that the curve could be driven without experiencing lateral acceleration discomfort.

This procedure and criteria for advisory speed determination has become nearly universally accepted in the highway engineering profession and typically is used by most transportation agencies. However, there has been concern that the ball-bank method of determining advisory speeds may be out-dated and not the best procedure. The need to update the procedures and criteria has been noted by the highway community for a number of years. Recognizing the age of the research, minor variations have been made in the criteria and its application in some roadway jurisdictions (3).

Many motorists also have observed that advisory speed signing is overly conservative and many exceed the posted advisory speeds. At least in part, this lack of credibility of curve advisory speeds may be due to the tendency in some jurisdictions to post advisory speeds below those that would be called for by the current ball-bank criteria. Another factor is that current vehicles have suspension and steering systems that are significantly improved providing better stability, cornering capabilities and driving comfort compared with typical vehicles at the time of the initial research. Therefore, it is appropriate to review the whole procedure and practice for determining advisory speeds. Any changes in advisory speed procedures and practices should be accompanied by a public information effort to re-educate the driving public until drivers again respect this type of advisory sign (4).

The following guidelines establish new values that satisfy the motorists’ needs. The current research has been reviewed with three methods addressed to determine an acceptable advisory speed. The recommended criteria have been adjusted to represent the current driving practices. While it is recognized that most roadways are
posted with advisory speeds based on the older criteria, it appears logical to raise the values to provide realistic postings that are compatible with driving practices. The new criteria will require a complete engineering restudy of the advisory speeds on existing roadways which will significantly impact all of the nations’ road jurisdictions.

While this effort may be considered onerous, in most cases the currently posted advisory speeds probably have not been restudied for many years. The provisions of the new *Manual on Uniform Traffic Control Devices* (13) encourage a restudy of the horizontal alignment signing. The *Manual on Uniform Traffic Control Devices* has a liberal compliance period of at least 10 years to implement the new horizontal alignment signing, so the engineering studies for curve advisory speeds can be done over a period of several years on a systematic basis with appropriate publicity so the public understands the revisions. Drivers will have to modify their driving habits so they do not incorrectly assume that posted advisory speeds can be driven at a higher speed. However, an adequate factor of safety is addressed in the new criteria so drivers even assuming a higher speed is acceptable should not be subjected to undue hazards. The older postings, while usually a lower speed, can remain in place until the new engineering study is completed and signs installed. It will be desirable to change all advisory speed plaques along a roadway at the same time to minimize motorist confusion.

**Background**

The timing was appropriate to review curve advisory speed practices based on the recent research and widespread concerns. A Task Force within the National Committee on Uniform Traffic Control Devices was appointed to review the available research and provide recommendations for updating the procedures. The major concerns and suggested changes addressed in the research studies fall within the following areas:

- The ball-bank indicator method may not be current nor the best method for determining advisory speeds (5).
- The current practice results in advisory speeds that are too conservative and are far below the 85th percentile speed of drivers traversing the curves (5)(6)(7).
• Current vehicle suspension and cornering capabilities are substantially better than those of vehicles that were used to determine the older criteria (8). As a result, drivers today can comfortably drive curves at speeds higher than those that would have been comfortable with older vehicles.

• The criteria for curve advisory speeds should be comparable to the design criteria in the AASHTO Policy on Geometric Design for Highways and Streets (9).

• The curve advisory speed practices in some jurisdictions have deviated from an adequate and universally accepted criteria resulting in posted advisory speeds well below prevailing curve speeds (3)(6). This results in inconsistent curve advisory speed postings from one jurisdiction to another.

• The current criteria do not consider truck advisory speeds and truck roll-over considerations (10)(11).

• Some inconsistencies have been noted in comparing current ball bank criteria with side friction factors used for curve design(8).

The research generally documented that drivers are often exceeding the existing posted advisory speeds by 7 to 10 miles per hour. An increase of 2 degrees for ball-bank indicator readings and comparable side friction factors is equivalent to 8 to 10 miles per hour increase in advisory speeds. The application of an accelerometer that measures lateral acceleration provides a direct determination of side friction factors and accommodates new instrumentation for advisory speed determinations. Minor adjustments in the relationship between ball-bank readings and side friction factors makes the ball-bank procedure and accelerometer determinations comparable. The use of the horizontal curve design speed equation remains an acceptable procedure using the newly recommended side friction factors.

There appears to be no reason to limit the advisory speed determination methods but instead recognize that any of the three methods are acceptable: the traditional ball-bank indicator, design speed equation, and accelerometer. The expansion of acceptable determination methods and change in criteria should offset current procedural deviations with the new Manual on Uniform Traffic Control Devices requirements encouraging
wider and universal application of acceptable advisory speeds. The recommended criteria for advisory speed determinations are as follows:

Table 2. Recommended Criteria for Curve Advisory Speed Determination
(Source: Adapted from Carlson and Mason 1999, Ref. 8)

<table>
<thead>
<tr>
<th>Speeds (mph)</th>
<th>Ball Bank Reading</th>
<th>Lateral Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 20</td>
<td>16°</td>
<td>0.28</td>
</tr>
<tr>
<td>25 – 30</td>
<td>14°</td>
<td>0.24</td>
</tr>
<tr>
<td>≥ 35</td>
<td>12°</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The new criteria are comparable to the current AASHTO design criteria. Some research has proposed higher values, but those values result in advisory speeds that exceed the observed speeds of drivers in curves, are above comfortable lateral acceleration levels, and reduce the margin of safety. Studies show that maximum side friction factors developed between passenger car tires and wet pavement in poor condition can be as low as approximately 0.35 at high speeds (9)(14).

For large trucks, there is a potential danger of overturning if the truck enters a curve at too high a speed. For sharp curves, such as loop exit ramps, it may be necessary to post truck advisory speeds. Current research indicates that truck overturning situations are limited and inconsistent when side friction factors are less than 0.35 (12). Theoretically, truck advisory speeds could be determined based on a side friction factor of 0.21, or a ball-bank reading of 12 degrees, and still provide a reasonable overturning safety factor below the 0.35 overturning threshold. But this assumes that the truck follows the exact radius of the curve which is unlikely in actual practice. Most drivers make steering corrections as they traverse a curve, sometimes steering a radius larger than the actual curve radius, sometimes steering a radius sharper than the actual curve radius. It must be recognized that if the truck is steered on a radius of ⅔ to ¾ of the actual curve radius, then the safety factor below the overturning threshold nearly disappears. As a
result, it is recommended that the criteria for posting truck advisory speeds be based on a side friction factor of 0.17, or a ball-bank reading of 10 degrees, for all speed ranges to ensure a reasonable overturning safety factor. This would result in truck advisory speeds below the advisory speeds determined for passenger cars.

**Determining Advisory Speeds Using the Design Speed Equation**

The design of highway curves is based on the relationship between design speed, radius of curvature, superelevation, and side friction (centripetal acceleration). The mathematical relationship between these variables is given by the equation (9):

\[ V = \sqrt{15R(0.01e + f)} \]

Where:
- \( V \) = Design speed (mph)
- \( R \) = Curve radius (feet)
- \( e \) = Superelevation (%)
- \( f \) = Side friction factor

The same equation can be used to calculate the advisory speed for a curve, if the curve radius and superelevation are known. The side friction factor is the same as lateral acceleration (measured in “g’s”), and is based on driver comfort. For highway design, side friction factors are set by AASHTO geometric design policies, and are generally in the range of 0.08 to 0.30 depending on design speed. As previously discussed, recent studies have suggested that the values in the current design manual are overly conservative, and when this equation is used to determine the advisory speed for a curve, the lateral acceleration rates contained in Table 2 can be used. This equation may have to be solved iteratively because the value for the side friction factor, \( f \), is different for different ranges of advisory speed, \( V \). For example, suppose that a curve has a 200-foot radius and a superelevation of 4%. If it is initially assumed that the value of the lateral acceleration is 0.21 (applicable for passenger car advisory speeds of 35 mph or more), the calculated advisory speed is 27 mph. This means that the lateral acceleration value should have been 0.24 (applicable for advisory speeds of 25 to 30 mph), and the advisory
speed is recalculated as 29 mph. Calculated advisory speeds should be rounded to the nearest 5 mph increment, so a 30 mph advisory speed would be used for this curve. The rounded passenger car advisory speeds calculated for various combinations of superelevation and curve radius are shown in Table 3.

### Table 3. Rounded Passenger Car Advisory Speeds (mph)

Based on Design Speed Equation

<table>
<thead>
<tr>
<th>Radius (ft)</th>
<th>Superelevation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-2</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>200</td>
<td>25</td>
</tr>
<tr>
<td>400</td>
<td>35</td>
</tr>
<tr>
<td>600</td>
<td>40</td>
</tr>
<tr>
<td>800</td>
<td>50</td>
</tr>
<tr>
<td>1000</td>
<td>55</td>
</tr>
</tbody>
</table>

In some cases, the curve radius and superelevation can be taken from as-built plans for a roadway that has been constructed fairly recently. However, it must be considered that a roadway that has been in service for many years may have been resurfaced one or more times since original construction. As a result of resurfacing, the superelevation of the curve may have changed, and the original plans may no longer be representative of field conditions. In other cases, the original plans may no longer be available.

If aerial photography is available, the curve radius can be determined by comparing circular curve templates with the aerial photograph. In the field, the approximate curve radius can be determined by the chord and middle ordinate method of measurement. This is illustrated in Figure 1. To determine the curve radius, measure a chord of any
convenient length (usually 100 feet), straight across from one point on the edge of the road to another point on the edge of the road within the curve (line AB in Figure 1) where the curvature is uniform. Also measure the middle ordinate from the center of the chord to the edge of the road (line CD in Figure 1). The radius of the curve can be calculated as:

\[ R = \frac{l^2}{8h} + \frac{h}{2} \]

Where:
- \( R \) = Curve radius (feet)
- \( l \) = Chord length (feet)
- \( h \) = Middle ordinate (feet)

The precision of this calculation is obviously limited by the ability to accurately measure the middle ordinate which would be as small as 1.25 feet (assuming a chord of 100 feet) for a curve with a radius of 1000 feet.

The superelevation can be measured in the field using a 4-foot carpenter’s level. As illustrated in Figure 2, position the level across the lane. With one end of the level on the road surface, measure the vertical distance from the road surface to the other end of the level. The cross slope of the roadway can then be calculated as the vertical distance divided by the length of the level. The superelevation should be measured in several locations along the curve, since it may vary. Also, the superelevation should be measured separately for each lane of the roadway.
Another method for determining the superelevation in the field is to stop a vehicle equipped with a ball-bank indicator (discussed in the next section) on the curve and read the degrees of deflection on the ball-bank. The superelevation is calculated as:

\[ e = (\tan D) \times 100\% \]

Where: \( e \) = Superelevation (%)
\( D \) = Degrees of deflection on ball-bank indicator

Again, this measurement should be made at several locations within the curve, and should be measured separately for each lane.

**Ball-Bank Indicator Method**

Advisory speeds may be determined in the field using a vehicle equipped with a ball-bank indicator and an accurate speedometer. The simplicity of this technique has led to its widespread acceptance as a guide to determining advisory speeds for changes in horizontal alignment. Figure 3 shows a typical ball-bank indicator.
The ball-bank indicator consists of a curved glass tube which is filled with a liquid. A weighted ball floats in the glass tube. The ball-bank indicator is mounted in a vehicle, and as the vehicle travels around a curve the ball floats outward in the curved glass tube. The movement of the ball is measured in degrees of deflection, and this reading is indicative of the combined effect of superelevation, lateral (centripetal) acceleration, and vehicle body roll. The amount of body roll varies somewhat for different types of vehicles, and may affect the ball-bank reading by up to 1°, but generally is insignificant if a standard passenger car is used for the test. Therefore, when using this technique, it is best to use a typical passenger car rather than a pickup truck, van, or sports utility vehicle. Also, the ball-bank indicator test is normally a two-person operation, one person to drive and the other to record curve data and the ball-bank readings, especially if advisory speeds are being determined for a series of curves.

Figure 3. Ball-bank Indicator
(Photo by R. Seyfried)
To ensure proper results, it is critical that the following steps be taken before starting test runs with the ball-bank indicator:

- Inflate all tires to uniform pressure as recommended by the vehicle manufacturer
- Calibrate the test vehicle’s speedometer
- Zero the ball-bank indicator

The vehicle speedometer should be calibrated to ensure proper and consistent test results. This can be done by checking the vehicle speed with a radar or laser speed meter, or by timing the vehicle over a measured distance (such as milepost spacing). Alternatively, a moving radar unit can be used to measure speed while conducting the ball-bank test runs rather than relying on the vehicle’s speedometer.

The ball-bank indicator must be mounted in the vehicle so that it displays a 0° reading when the vehicle is stopped on a level surface. The positioning of the ball-bank indicator should be checked before starting any test. This can be done by stopping the car so that its wheels straddle the centerline of a two-lane highway on a tangent alignment. In this position, the vehicle should be essentially level, and the ball-bank indicator should give a reading of 0°. It is essential that the driver and recorder be in the same position in the vehicle when the ball-bank indicator is set to a 0° reading as they will be when the test runs are made because a shift in the load in the vehicle can affect the ball-bank indicator reading.

Starting with a relatively low speed, the vehicle is driven through the curve at a constant speed following the curve alignment as closely as possible, and the reading on the ball-bank indicator is noted. On each test run, the driver should reach the test speed at a distance of at least ¼ mile in advance of the beginning of the curve, and maintain the same speed throughout the length of the curve. The path of the car should be maintained as nearly as possible in the center of the inner-most lane (the lane closest to the inside edge of the curve) in the direction of travel. If there is more than one lane in the direction of travel, and these lanes have differing superelevation rates, drive in the lane with the lowest amount of superelevation. Because it is often difficult to drive the exact radius of
the curve and keep the vehicle at a constant speed (cruise-control helps to maintain a constant speed), it is recommended that at least three test runs in each direction be made to more accurately determine the ball-bank reading for any given speed. On each test run, the recorder must carefully observe the position of the ball throughout the length of the curve and record the deflection reading that occurs when the vehicle is as nearly as possible driving the exact radius of the curve.

If the reading on the ball-bank indicator for a test run does not exceed an acceptable level (as indicated by the recommended criteria in Table 2), then the speed of the vehicle is increased by 5 mph and the test is repeated. The vehicle speed is repeatedly increased in 5 mph increments until the ball-bank indicator reading exceeds an acceptable level. The curve advisory speed is set at the highest test speed that does not result in a ball-bank indicator reading greater than an acceptable level.

Figure 4 is an example of a data collection form that can be used to record the results of ball-bank indicator test runs. In the example in Figure 4, test runs were started at 25 mph, with ball-bank indicator reading of about 6°. This is well below the suggested criteria of 14° for a speed of 25 mph. The speeds of the test runs were gradually increased until the speed of 35 mph gave readings of 10° to 12°. These are the highest readings attained without exceeding an the suggested criteria of 12° for a speed of 35 mph or more. This study would result in posting an advisory speed of 35 mph for both directions of travel for this curve. Several alternative field data collection and supervisor approval forms are shown in the Appendix.

**Accelerometer**

An accelerometer is an electronic device which can measure the lateral (centripetal) acceleration experienced by a vehicle as it travels around a curve. Lateral acceleration can be directly correlated with ball-bank indicator readings (8). The lateral accelerations that correspond to the recommended ball-bank indicator criteria are shown in Table 2. The lateral acceleration criteria in Table 2 are measured in “g’s,” acceleration due to
### BALL-BANK INDICATOR STUDY

**LOCATION:** STATE ROUTE 43  
**COUNTY:** DAVIS  
**SECTION:**  
**POSTED SPEED (MPH):** 55  
**PAVEMENT CONDITION:** DRY  
**DATE:**  
**VEHICLE:** 2008 CHEVROLET IMPALA  
**DRIVER:** SEYFRIED  
**RECORDER:** PLINE  

**REMARKS:**

<table>
<thead>
<tr>
<th>DIRECTION OF TRAVEL</th>
<th>MILEPOST</th>
<th>SPEED (MPH)</th>
<th>BALL-BANK READING (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>START CURVE</td>
<td>END CURVE</td>
<td>RUN 1</td>
</tr>
<tr>
<td><strong>NORTH</strong></td>
<td>8.32</td>
<td>8.65</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td><strong>SOUTH</strong></td>
<td>8.65</td>
<td>8.32</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 4. Sample Ball-Bank Indicator Data Collection Form
gravity (32.2 feet/second/second). Thus a lateral acceleration of 0.28g is equal to 0.28 x 32.2 ft/sec/sec = 9.02 ft/sec/sec.

An example of a commercially available accelerometer is shown in Figure 5. The accelerometer is mounted on a level surface in a standard passenger vehicle such as the top of the dashboard. Some accelerometers are designed specifically for determining curve advisory speeds and directly correlate the lateral acceleration measured in the curve with the corresponding ball-bank indicator reading, and provide an output in ball-bank indicator degrees of deflection. The device may also have a self-leveling feature.

Figure 5. Accelerometer
(Source: Rieker Electronics, Inc.)
Similar to a ball-bank indicator study, the vehicle is driven around the curve at a constant speed following the radius of the curve as closely as possible. The advisory speed of the curve is set at the highest speed that can be driven without exceeding a comfortable lateral acceleration. The accelerometer does not require a second person to act as recorder because the data are stored for later recall, or the data can be transferred directly into a portable computer.

There have been some problems reported in the use of accelerometers if the device is too sensitive. Small changes in steering, or even bumps or dips in the pavement, can cause up to a 2° change in the ball-bank indicator reading from such an accelerometer. This would be similar to trying to use a ball-bank indicator that did not have a liquid in the curved glass tube to dampen the movement of the ball. Desirably, the device should dampen fluctuations in readings to produce a smoothing of the data. A sample field data collection form for use with an accelerometer can be developed similar to the ball-bank indicator forms in the Appendix.

**Establishing Advisory Speeds**

Using any of the three methods noted above should result in the same advisory speed for a curve. It is important to reiterate that the advisory speed criteria are based on driver comfort, not safety. A sufficiently skillful driver may be able to traverse a curve on dry pavement at a speed considerably higher than the advisory speed without exceeding the friction capabilities of the pavement. However, most drivers would choose not to drive at a higher speed because they would experience uncomfortable levels of lateral acceleration.

The *Manual on Uniform Traffic Control Devices* (13) indicates that the “advisory speed shall be determined by an engineering study that follows established engineering practices” (Section 2C.08). The Manual further defines an engineering study as “the
comprehensive analysis and evaluation of available pertinent information, and the application of appropriate principles, Standards, Guidance, and practices as contained in this Manual and other sources, for the purpose of deciding upon the applicability, design, operation, or installation of a traffic control device. An engineering study shall be performed by an engineer, or by an individual working under the supervision of an engineer, through the application of procedures and criteria established by the engineer. An engineering study shall be documented” (Section 1A.13).

Therefore, the establishment of advisory speeds must follow standard procedures developed and adopted by the engineering personnel of an agency. All field work used for determining the advisory speeds must be performed under the supervision of an engineer. Finally, the data collected and analysis performed must preserved in written documentation. The Appendix contains a sample curve advisory speed study supervisor approval form that can be used to document the field data collection.

The maximum comfortable operating speed on a curve can be determined using any of the three methods discussed above (design speed equation, ball-bank indicator, or accelerometer). The advisory speed for the curve should be set at the 5-mph increment nearest to this maximum comfortable speed. The advisory speed to be posted should not be arbitrarily reduced below the comfortable speed determined using these methods, because an unrealistically low advisory speed will lose credibility among drivers, and create inconsistencies that may lead drivers into traveling at too high a speed through other curves.

Advisory speed plaques are only used in conjunction with appropriate warning signs, and never alone. Turn, Curve, Reverse Turn, Reverse Curve, and Winding Road signs are used in locations where it is desirable to warn drivers of changes in the horizontal alignment of the roadway. The *Manual on Uniform Traffic Control Devices* (13) indicates that the use of Turn or Reverse Turn signs should be limited to changes in alignment where the advisory speed is 30 mph or less. The Curve or Reverse Curve signs are intended for use where the advisory speed is greater than 30 mph.
Where a Reverse Curve warning sign or a Winding Road warning sign is used, the advisory speed should be based on the curve with the lowest comfortable operating speed. However, if one curve in the series has a dramatically lower comfortable speed, it would be desirable to place a separate warning sign with the appropriate advisory speed for that individual curve.

In some cases, there may be other factors that influence the selection of the advisory speed in addition to the comfortable operating speed on the curve. Available sight distance or deceleration distance (on an exit ramp) may, in some cases, require an advisory speed lower than the comfortable operating speed for the curve.

**Truck Advisory Speeds**

The appropriate warning signs for truck rollover concerns require more than just determination of truck advisory speeds. Large trucks, tank trailers and truck freight trailers have a high center of gravity and are susceptible to rollover crashes on a sharp curve. The loop ramps on freeway interchanges and direct freeway to freeway connections are sometimes subject to truck rollover problems. The potential for such crashes may increase because of radius of horizontal curvature, inadequate deceleration length or deficient specific signing. Truck rollover theoretically can occur when the lateral acceleration exceeds 0.30, but no calculated lateral acceleration less than 0.35 has been determined in any truck rollover collisions. It is recommended that a Ball Bank reading of 10 degrees (side friction = 0.17) be used to provide a reasonable factor of safety. This value is about half the critical side friction factor accommodating those occasions where the truck may exceed the posted truck advisory speed or the truck travels a curve radius that is less then the actual roadway curvature. These criteria will generally produce a truck advisory speed that is approximately 5 mph less than the advisory speeds determined for passenger cars, except for the lower speed ranges.
The *Manual on Uniform Traffic Control Devices*, Section 2C.13, Section 2C.14 and Table 2C-5, covers the use of the Truck Rollover Warning sign (W1-13), Advisory Exit Speed sign (W13-2), and the Advisory Ramp Speed sign (W13-3). The application of these signs shall be based on an engineering study that considers the roadway and operational characteristics that may contribute to a loss of vehicle control and potential truck rollovers. It is suggested that the engineering study for Truck Rollover Warning signs address the following considerations:

1. Speed data and advisory speed determinations.
2. Traffic characteristics.
4. Recommended traffic control devices.

It should be noted that any posted Advisory Speed for the Truck Rollover signing should reflect the truck advisory speed determination. The *Manual on Uniform Traffic Control Devices* provides a number of other devices that can be used in conjunction with the above signs to address truck rollover consideration such as:

- Chevron Alignment signs (W1-8)
- Combination Horizontal Alignment/Advisory Speed sign (W1-1a and W1-2a)
- One Direction Large Arrow sign (W1-6)
- Combination Horizontal Alignment/Advisory Exit and/or Advisory Ramp Speed Signs (W13-6 and W13-7)

Additionally, the warning can be enhanced with enlarged signing, a TRUCK header panel, flashing beacons and changeable message signs. The traffic engineering study should address the recommended signing for the specific field conditions.
REFERENCES


7. Anthony P. Voigt, David W. Fenno and Darrell W. Borchardt, Evaluation of Vehicle Speeds on Freeway to Freeway Connector Ramps in Houston, FHWA/TX-03-4318-1, Texas Transportation Institute, College Station, TX, October 2002.


Research Institute, FHWA-RD-89-226, Federal Highway Administration, McLean, VA, August 1990.


APPENDIX

SAMPLE FIELD DATA COLLECTION FORMS

1. Curve Advisory Speed Calculations
2. Ball-Bank Indicator Test Supervisor Approval
3. Ball-Bank Indicator Study Form
4. Ball-Bank Indicator Test Summation
5. Curve Advisory Speed Determination Field Data Sheet
Advisory Speed Approval

Jurisdiction: ______________________________________________________

Location: _________________________________________________________

From: __________________________ To: ____________________________

Project No./Title: _________________________________________________

Advisory Speed Study Attached:

  Ball Bank Indicatory Study _____ Date:______________

  Speed Formula Calculations _____ Date:______________

  Accelerometer Readings _____ Date:______________

Completed By: _______________________________ Date:______________

Study Approval:

Name: ________________________________ Title:_____________________

Date:________________________
Curve Advisory Speed Calculations

Sheet ___ of ____

Completed By: _______________________________ Date: ______________

Jurisdiction:____________________________________________________

Location:_______________________________________________________

From: __________________________ To: ____________________________

Project No./Title: _________________________________________________

\[ V = \sqrt{15R(0.01e + f)} \]

<table>
<thead>
<tr>
<th>DIRECTION OF TRAVEL</th>
<th>CURVE BEGIN STA.</th>
<th>CURVE END STA.</th>
<th>CURVE RADIUS (ft)</th>
<th>SUPER-ELEVATION (%)</th>
<th>SIDE FRICTION</th>
<th>ADVISORY SPEED (mph)</th>
<th>WARNING SIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

Remarks: _______________________________________________________

Study Approval:

Name: ________________________________ Title:_____________________

Date: ______________

9/29/2009
# BALL-BANK INDICATOR STUDY

LOCATION:  
COUNTY:  
SECTION:  
POSTED SPEED (MPH):  
PAVEMENT CONDITION:  
DATE:  
VEHICLE:  
DRIVER:  
RECORDER:  
REMARKS:  

<table>
<thead>
<tr>
<th>DIRECTION OF TRAVEL</th>
<th>MILEPOST</th>
<th>SPEED (MPH)</th>
<th>BALL-BANK READING (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>START CURVE</td>
<td>END CURVE</td>
<td>RUN 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
BALL BANK INDICATOR TEST SUMMATION

Jurisdiction: _______________________________ Date: ________________

Location: __________________________________________________________________

Weather: ___________________ Road Surface: __________________

Driver: _________________________ Recorder: _______________________

Vehicle: ________________________ Posted Speed Limit: ______________

Direction: _____________ Begin Curve: _________ End Curve: _________

Show each vehicle test run as a dot on the graph
**CURVE ADVISORY SPEED DETERMINATION FIELD DATA SHEET**

<table>
<thead>
<tr>
<th>Highway:</th>
<th>County:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section:</td>
<td>Date:</td>
</tr>
<tr>
<td>Posted Speed (mph):</td>
<td>Pavement Condition:</td>
</tr>
<tr>
<td>Vehicle:</td>
<td>Driver/Recorder:</td>
</tr>
<tr>
<td>Remarks:</td>
<td></td>
</tr>
</tbody>
</table>

**BALL BANK READINGS:** 12 degrees for speeds of 35 mph or more  
14 degrees for speeds of 25 to 30 mph  
16 degrees for speeds of 20 mph or less

<table>
<thead>
<tr>
<th>Direction of Travel</th>
<th>Curve Direction</th>
<th>Beg. Curve</th>
<th>End Curve</th>
<th>Tangent Length</th>
<th>Ball Bank Reading</th>
<th>Advisory Speed (mph)</th>
<th>Curve Warning Sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT</td>
<td>RT</td>
<td>MP</td>
<td>MP</td>
<td>Miles</td>
<td>Degrees</td>
<td>Current</td>
<td>Recommended</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sign No.</td>
</tr>
</tbody>
</table>

9/29/2009
Session 7

Reduce the Consequences of Leaving the Roadway

Session 7 Learning Outcomes:

• Select countermeasures to reduce the severity of Roadway Departure crashes
15.2 B1 Design safer slopes and ditches to prevent rollovers (P)

15.2 B - Minimize the adverse consequences of leaving the roadway at a horizontal curve
15.2 B1 Design safer slopes and ditches to prevent rollovers

<table>
<thead>
<tr>
<th>Sideslope Before Condition</th>
<th>Sideslope After Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1:4</td>
</tr>
<tr>
<td></td>
<td>SV</td>
</tr>
<tr>
<td>1:2</td>
<td>10</td>
</tr>
<tr>
<td>1:3</td>
<td>8</td>
</tr>
<tr>
<td>1:4</td>
<td>0</td>
</tr>
<tr>
<td>1:5</td>
<td>-</td>
</tr>
<tr>
<td>1:6</td>
<td>-</td>
</tr>
</tbody>
</table>

15.2 B2 Remove/Relocate Roadside Objects

15.2 B2 Reduce hazards associated with fixed roadside objects
AASHTO Recommendation on Horizontal Curves

- AASHTO recommends extending the width of the clear zone on the outside of the curves to the left.
Horizontal Curves

Clear Zone Example:

- Assume a curve with a radius of 1430 feet
- A design speed of 55 mph
Horizontal Curve Adjustments

<table>
<thead>
<tr>
<th>RADIUS [ft]</th>
<th>DESIGN SPEED [mph]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>2860</td>
<td>1.1</td>
</tr>
<tr>
<td>2260</td>
<td>1.1</td>
</tr>
<tr>
<td>1910</td>
<td>1.1</td>
</tr>
<tr>
<td>1640</td>
<td>1.1</td>
</tr>
<tr>
<td>1450</td>
<td>1.1</td>
</tr>
<tr>
<td>1270</td>
<td>1.2</td>
</tr>
<tr>
<td>1159</td>
<td>1.2</td>
</tr>
<tr>
<td>950</td>
<td>1.2</td>
</tr>
<tr>
<td>820</td>
<td>1.3</td>
</tr>
<tr>
<td>720</td>
<td>1.3</td>
</tr>
<tr>
<td>640</td>
<td>1.3</td>
</tr>
<tr>
<td>570</td>
<td>1.4</td>
</tr>
<tr>
<td>360</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Countermeasures for Relocation of Utility Poles

Relocate Utility Pole Behind Guard Rail – Not in Front!

<table>
<thead>
<tr>
<th>Pole Offset</th>
<th>UP ACC/MI/YR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.0</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Reducing the Consequences of Leaving the Roadway

**Crash Modification Factors (%)**

<table>
<thead>
<tr>
<th>Pole Offset Before (feet)</th>
<th>Pole Offset After (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

"The Influence of Utilities on Roadside Safety" has been published as TRB State of the Art Report No. 9.

---

**Utility Pole Model Quantifies Pole Removal/Relocation Strategies**

<table>
<thead>
<tr>
<th>ADT</th>
<th>Lane Width (ft)</th>
<th>N = 50 Poles Per Mi</th>
<th>N = 50 Poles Per Mi</th>
<th>N = 80 Poles Per Mi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pole Distance from Road (ft)</td>
<td>Pole Distance from Road (ft)</td>
<td>Pole Distance from Road (ft)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5</td>
<td>10</td>
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<tr>
<td>1,000</td>
<td>9</td>
<td>.97</td>
<td>.95</td>
<td>.93</td>
</tr>
<tr>
<td>2,000</td>
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<td>.93</td>
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</tr>
<tr>
<td>5,000</td>
<td>9</td>
<td>.97</td>
<td>.95</td>
<td>.93</td>
</tr>
<tr>
<td>10,000</td>
<td>9</td>
<td>.95</td>
<td>.93</td>
<td>.91</td>
</tr>
</tbody>
</table>
Utility Pole Model Quantifies Pole Removal/Relocation Strategies

Figure 18. Nomograph for predicting utility pole accident frequency (96).
Source – NCHRP 440

7-19

7-20
Reducing the Consequences of Leaving the Roadway

**Percent Reduction for Relocation of Roadside Hazards**

<table>
<thead>
<tr>
<th>Increase in Obstacle Distance (L.O.D.), m</th>
<th>Trees (%)</th>
<th>Mailboxes, Culverts, &amp; Slips (%)</th>
<th>Guardrail (%)</th>
<th>Fence/Gate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 (3)</td>
<td>22</td>
<td>14</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>1.5 (5)</td>
<td>34</td>
<td>23</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>2.4 (8)</td>
<td>49</td>
<td>23</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>3.3 (10)</td>
<td>57</td>
<td>34</td>
<td>70</td>
<td>44</td>
</tr>
<tr>
<td>4.8 (15)</td>
<td>65</td>
<td>46</td>
<td>78</td>
<td>52</td>
</tr>
<tr>
<td>4.6 (15)</td>
<td>71</td>
<td>N.P.</td>
<td>N.F.</td>
<td>N.F.</td>
</tr>
</tbody>
</table>

Notes:
- N.P. = generally not feasible to relocate obstacles to specified distances.
- L.O.D. = amount of increase in obstacle distance from roadway.
- This table is appropriate only for obstacle distances of 9.1 m (30 ft) or less and only on two-lane rural roadways.

NCHRP 440 – Accident Mitigation Guide for Congested Rural Two-Lane Highways
15.2 B3 Delineate roadside objects

15.2 B3 - Minimize the adverse consequences of leaving the roadway at a horizontal curve

Delineate Roadside Objects
Reducing the Consequences of Leaving the Roadway

Delineate Roadside Objects

Delineate Roadside Objects
15.2 B4 Add or Improve Roadside Hardware

- If necessary, protect fixed object hazards by adding breakaway hardware or appropriate barrier system

- Upgrade obsolete hardware systems to current standards

Replace/Relocate Non-Crashworthy Sign Supports

- **Sign Supports are required to be crashworthy**

- **Acceptable Sign Supports for small signs from Traffic Control Devices Handbook, ITE**
Replace/Relocate Non-Crashworthy Sign Supports

Small sign Supports – less than 50 Sq Foot
Two 1 ½” Holes in a 4” x 6” wood post

Update/Replace Roadside Hardware
Barrier Design for Horizontal Curves

![Diagram of barrier design for horizontal curves]

- LA: Edge of Traveled Way
- PT: Point of Tangency
Length of Need on the Inside of a Horizontal Curve

- SHOULDER
- SHOULDER
- HAZARD

EXIT 27

25 MPH
Reducing the Consequences of Leaving the Roadway

Very Tight Left Cross-Over

Inspection Shows Several Impacts

Records Show Several Fatalities

Sometimes we try to apply solutions but the solutions do not correct the problem.

Wide Sand Barrel Array Helps

But Impacts Still Occur On Barrier
A SOLUTION for Some of These Conditions

An Energy Absorbing Wall to Cushion to Errant Motorists Impacts

Safe-T-Curve™ Barrier
Typical Application
Session 7 Review:

• The clear zone can be extended along the outside of curves (True / False)
Session 7 Review:

- 2 primary strategies to reduce crashes into utility poles that cannot be removed

Session 7 Learning Outcomes:

- Select countermeasures to reduce the severity of Roadway Departure crashes
Questions and Discussion
Session 8

Case Studies and Deployment Strategies

Session 8 Learning Outcomes:

• Describe application Case Studies of Safety Measures for Horizontal Curves
Systematic Deployment

• Traditionally the safety improvement program has concentrated on addressing the highest crash locations in the jurisdiction. Improvements have been implemented, mainly at intersections and curves.

• Because of the relatively small number of improvements, the reduction in statewide numbers of deaths and serious injuries is almost negligible.
• If we are to lower the statewide numbers of deaths and injuries, an additional effort of systematically applying low-cost, cost-effective improvements at a large number of locations with documented crash histories needs to be pursued.
Systematic Deployment

- Consider County- or District-wide contracts to implement designated improvements at large numbers of locations that can be favorably impacted by the improvements.

Methods of Targeting Potential Safety Improvements

- Spot
- Corridor
- System Level
Spot Analysis

- Target spot locations identified (high crash locations / black spots etc)
- Evaluate: type; severity and PCC’s or other circumstances of crashes
- Investigate crashes for data emphasis selected

Spot Analysis

- Develop stand alone safety improvements
- Develop educational programs for identified problems
- Targeted enforcement efforts
## Methods of Targeting & Potential Safety Improvements

### Spot - Curves
- Target - crash frequency higher than the average or severity index above average, or other.
  - Bring all curves up to “Nominal”
  - Signing/Marking
  - Install Chevrons, Large Arrow sign or Delineators on all curves
  - Install wider or Durable Pavement Markings on curves
  - Relocate Utility Poles

### Methods of Targeting & Potential Safety Improvements

### Spot - Curves
- Target - crash frequency higher than the average or severity index above average, or other.
  - Install Rumble Strips/Stripes on Curves.
  - Install Guardrail with bad roadside, high hazard index
  - Improve roadside
### Corridor Analysis

- Joint safety improvements by multiple Counties
- Develop educational programs for identified problems
- Targeted enforcement efforts

### Corridor Analysis

- Target highway corridors in counties
- Evaluate: frequency; type; severity and PCC’s or other circumstances of crashes
- Investigate crashes for data emphasis selected
- Target improvement projects for inclusion of problems/deficiencies identified
Methods of Targeting & Potential Safety Improvements

- Corridor - Curves
  Target – all curves on a highway segment with a Delta Speed of => 15mph (55mph to 40 MPH) – High Risk
  - Bring all curves up to “Nominal” Signing/Marking
  - Install Chevrons or Delineators on all curves
  - Install wider or Durable Pavement Markings on curves
  - Relocate utility poles

Methods of Targeting & Potential Safety Improvements

Corridor - Curves
  Target – all curves on a highway segment with a Delta Speed of => 15mph (55mph to 40 MPH) – High Risk
  - Install Rumble Strips/Stripes on Curves
  - Install Guardrail with bad roadsides
  - Improve roadside
## Systems Analysis

- Target an entire class of highway countywide
- Evaluate: frequency; type; severity and PCC’s or other circumstances of crashes
- Investigate commonality in crashes for data emphasis selected

<table>
<thead>
<tr>
<th><img src="image1.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8-15</strong></td>
</tr>
</tbody>
</table>

## Systems Analysis

- Develop standards or operations changes
- Implement safety and operational improvements
- Develop educational programs for broad ranging crash themes

<table>
<thead>
<tr>
<th><img src="image2.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8-16</strong></td>
</tr>
</tbody>
</table>
## Methods of Targeting & Potential Safety Improvements

**System**

| Target – all curves in a County with a Delta Speed of => 15mph (55mph to 40 MPH or less) – High Risk Curves |
| Bring all curves up to “Nominal” |
| Signing/Marking |
| Install Chevrons or Delineators on all curves |
| Install wider or Durable Pavement Markings on curves |
| Relocate utility poles |

## Methods of Targeting & Potential Safety Improvements

**System**

| Target – all curves in a County with a Delta Speed of => 15mph (55mph to 40 MPH or less) – High Risk Curves |
| – Install Rumble Strips/Stripes on Curves |
| – Install guardrail with bad roadside |
| – Improve roadside |
Iowa’s High-Crash Curve Program

- 115,000 miles of public roadway (13th in U.S.)
- Roadway Departure crashes account for 61% of Iowa’s fatalities
  - Average 52 curve fatal crashes/year (13%)
- Receives approx. $20M in state and federal safety funds
  ➢ Targeted, systematic approaches provide the best results
Systematic Approach

- High-quality crash reporting, collection, and analysis systems.
- Top 5% Transparency Reports
- Engineering AND behavioral issues:
  - Single-vehicle ROR
  - MV cross-median
  - Intersection
  - Unbelted
  - Alcohol/Drug
  - Speed

Identifying High-Crash Curves

- Two methods developed by the Institute for Transportation (InTrans) at Iowa State University, with funding and guidance from the Iowa Department of Transportation Office of Traffic and Safety
  - Initial effort (2001, 10 years of crash data)
  - Revised method (2009, 7 years of crash data)
Initial Analysis – State System

- Statewide average = 1.1 / MVM (avg radius = 2850 ft., avg length = 870 ft.)
- Top 30 average = 11.7 (7.2*) / MVM (avg radius = 1780 ft., avg length = 807 ft.)
- Worst (of top 30) = 78 / MVM
  - 5% of crashes occurred at top 30 locations (1% of curves)
  - 11% of fatalities occurred at top 30 locations

*Weighted average

Revised Analysis
State & Local System

- Created a High-Crash Curve Database:
  - Used GPS data from pavement management program
  - Used a line simplification algorithm to determine curve locations
  - Overlaid seven years of crash data
  - Applying the process to other states’ databases
Identifying High-Crash Curves

- 200+ curves identified and ranked by frequency and severity
- Crashes were color-coded and plotted on an aerial photograph for review and confirmation

Top 30 High-Crash Curves

Preliminary Top 30 High Crash Horizontal Curves
Two lane and paved secondary roads 2001 to 2007

* Based on the frequency of non-animal, non-intersection crashes.
Possible Low-Cost Improvements

- Install/replace curve and chevron signs with bigger/brighter/florescent
- Pave inside & outside shoulders w/ rumble strips
- Enhanced pavement markings – tape, all-weather paint, EL rumble stripe
  - 4-inch ELRS county pilot
- Resurface thru curve and add CL & EL rumble stripes

Implementation

- Counties and DOT Districts have either already deployed countermeasures or have secured safety funding for improvements
One Example

- 9-degree curve
- 30 x 36” Chevrons
- 40% Reduction – All Crashes
- -57% reduction Night Crashes
- Significant reduction in severity

Iowa’s High Risk Rural Road Program

- Program administered by Iowa DOT Office of Local Systems
- Approx. $1.15M/year designated for safety improvements on IA high-risk rural roads
- HRRRs are defined as paved roads, classified as rural major collectors, rural minor collectors or rural local roads, with a fatal and major injury crash rate above the statewide average
- Identified the need to reduce ROR crashes at curves
Iowa’s HRRR Program

- **Curve Signing Program (Phase I)**
  - $23,000 per county made available
  - Curve ahead, advisory speed plaques, and chevrons
  - Signs had to be microprismatic and fluorescent yellow
  - 100% federal participation in signs, posts, and mounting hardware
  - Counties match was donating the labor and equipment to install the signs
  - Application including inventory of needed signs was required
  - If curve signing adequate, counties could apply for infrastructure improvements
Iowa’s HRRR Program

- Sign applications and inventory verified and compiled
- Solicited bids though Office of Purchasing
- 33 Counties (1/3) participated in Curve Signing
  - 3159 Signs
  - 349 Advisory Speed Plaques
  - 4002 Chevrons

Iowa’s HRRR Implementation
Minnesota Approach on County Roads

Minnesota Statewide Fatalities (2001-2005)

| Total Fatalities | 3,008 |
| Total Vehicle Occupant Fatalities | 2,429 |

**Driver Behavior Based Emphasis Areas**

<table>
<thead>
<tr>
<th>Emphasis Area</th>
<th>Fatality Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbelted (Based on Veh. Occ. Fatalities)</td>
<td>1</td>
</tr>
<tr>
<td>Alcohol-Related</td>
<td>2</td>
</tr>
<tr>
<td>Speeding-Related</td>
<td>5</td>
</tr>
<tr>
<td>Involved Drivers Under 21</td>
<td>6</td>
</tr>
</tbody>
</table>

**Infrastructure Based Emphasis Areas**

<table>
<thead>
<tr>
<th>Emphasis Area</th>
<th>Fatality Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Vehicle ROR</td>
<td>4</td>
</tr>
<tr>
<td>Intersection</td>
<td>3</td>
</tr>
<tr>
<td>Head-On and Sideswipe</td>
<td>7</td>
</tr>
</tbody>
</table>
Out State ATPs (2001-2005 Fatalities)

<table>
<thead>
<tr>
<th></th>
<th>Driver Behavior Based Emphasis Areas</th>
<th>Infrastructure Based Emphasis Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Fatalities</td>
<td>Unbelted</td>
</tr>
<tr>
<td>Statewide</td>
<td>3,008</td>
<td>1,271 (42%)</td>
</tr>
<tr>
<td>ATP Total</td>
<td>2,063</td>
<td>968 (47%)</td>
</tr>
<tr>
<td>State Trunk Highway</td>
<td>1,089 (53%)</td>
<td>476 (49%)</td>
</tr>
<tr>
<td>Local Roads</td>
<td>974 (47%)</td>
<td>492 (63%)</td>
</tr>
</tbody>
</table>

Example Safety Improvements

**Reactive**

Goal For Metro District

- High-Cost Improvements
  - Interchanges
  - Roundabouts

Goal For Out State Districts

- Low-Cost Intersection Improvements
  - Shorten Radius

- Low-Cost Roadway Improvements
  - Install Traffic Signs & Markings

**Proactive**

Goal For Metro District

- 50 / 50
  - Consider Management and Technology Improvements

- 50 / 50
  - Employ ITS Technologies, Efficient Speed Enforcement in School Zones
  - Access Management

Goal For Out State Districts

- Low-Cost Intersection Improvements
  - Install Traffic Signs & Markings

- Road Departure Improvements
  - Shoulder Width
  - Shoulder Width before and after
  - Shoulder Width Reduction
  - Improve Roadside Fences

**Example:** FHWA – Low Cost Treatments for Horizontal Curve Safety
A follow up study of over 200 curves on both the State and County highway system in Minnesota found:

- More than 50% of the curves had NO crashes during the Study period.
- The curves averaged between 0.1 and 0.2 crashes per year and the “worst” curve averaged 1.5 crashes per year.
- 90% of fatal crashes and 75% of injury crashes occurred on curves with radii less than 1,500 feet.
- Crash rates on curves with radii greater than 2,000 feet approximate the overall rate on 2-lane rural roads.
- As curve radii decrease, crash rates increase – the crash rate at 1,500 feet = 2x, at 1,000 feet = 5x and at 500 feet = 11x.

Additional Analysis to Support Priorities of CEAs in Freeborn County (2002-2006 Crash Data)

- During the 2002 to 2006 timeframe:
  - 65% of the crashes on conventional roads occurred on the county system
  - the most prevalent type of crash is lane departure and 75% of these occurred on the county system
  - lane departures accounted for 82% of the severe crashes and 92% of these occurred on the county system

Crash Data Overview

Source: MnDOT Crash Data, 2002-2006
Severe is fatal plus serious injury crashes.
Lane Departure Crashes
High Priority Horizontal Curves

• Priority Ranking
Based on:
  – Crashes
  – Radius
  – Visual Trap
  – Proximity to other Priority Curves

Example of Visual Trap in Meeker County

Example of a Visual Trap at a Horizontal Curve in Freeborn County
Enhanced Curve Delineation

- 57 curves
- $1,000/curve
- $57,000

Criteria
- ADT range between 1,000 and 2,500
- Severe Crash (K or A)
- Curve radius between 750 and 1,250
- Intersection in curve
- Visual trap
- Proximity to other priority curves

Curve Project List

<table>
<thead>
<tr>
<th>Enhanced Curve Delineation</th>
<th>Curves</th>
<th>Road Departure Crashes (275 total)</th>
<th>Total Curve Related (159 total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CSAM 14</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>CSAM 15</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>CSAM 16</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

FHWA – Low Cost Treatments for Horizontal Curve Safety
Session 8 Learning Outcomes:

- Described application Case Studies of Safety Measures for Horizontal Curves
Questions and Discussion
Introduction

This issue brief documents estimates of the crash reduction that might be expected if a specific countermeasure or group of countermeasures is implemented with respect to roadway departure crashes and other non-intersection crashes. The crash reduction estimates are presented as Crash Reduction Factors (CRFs).

Traffic engineers and other transportation professionals can use the information contained in this issue brief when asking the following types of question: Which countermeasures might be considered along a particular section of a highway that is experiencing a high number of roadway departure crashes? What changes in the number of roadway departure crashes can be expected with the implementation of the various countermeasures?

When selecting countermeasures to reduce the number and/or severity of roadway departure crashes, the practitioner should first consider countermeasures designed to reduce the likelihood of vehicles leaving the roadway. Next, the practitioner should select strategies which minimize the likelihood of crashing into an object or overturning if the vehicle travels beyond the edge of the shoulder. Finally, the practitioner should consider countermeasures which reduce the severity of the crash such as improving the design and application of barrier and attenuation systems.

When selecting countermeasures to reduce the number and/or severity of crashes associated with hazardous roadside obstacles, the practitioner should refer to the AASHTO Roadside Design Guide which recommends these design options in order of preference:

1. Remove the obstacle;
2. Redesign the obstacle so it can be safely traversed;
3. Relocate the obstacle to a point where it is less likely to be struck;
4. Reduce impact severity by using an appropriate breakaway device;
5. Shield the obstacle with a longitudinal traffic barrier designed for redirection or use a crash cushion; and
6. Delineate the obstacle if the above alternatives are not appropriate.

Crash Reduction Factors

A CRF is the percentage crash reduction that might be expected after implementing a given countermeasure. In some cases, the CRF is negative, i.e. the implementation of a countermeasure is expected to lead to a percentage increase in crashes.

One CRF estimate is provided for each countermeasure. Where multiple CRF estimates were available from the literature, selection criteria were used to choose which CRFs to include in the issue brief:

• Firstly, CRFs from studies that took into account regression to the mean and changes in traffic volume were preferred over studies that did not.
• Secondly, CRFs from studies that provided additional information about the conditions under which the countermeasure was applied (e.g. road type, area type) were preferred over studies that did not.
Where these criteria could not be met, a CRF may still be provided. In these cases, it is recognized that the reliability of the estimate of the CRF is low, but the estimate is the best available at this time. The CRFs in this issue brief may be periodically updated as new information becomes available.

The Desktop Reference for Countermeasures lists all of the CRFs included in this issue brief, and adds many other CRFs available in the literature. A few CRFs found in the literature were not included in the Desktop Reference. These CRFs were considered to have too large a range or too large a standard error to be meaningful, or the original research did not provide sufficient detail for the CRF to be useful.

A CRF should be regarded as a generic estimate of the effectiveness of a countermeasure. The estimate is a useful guide, but it remains necessary to apply engineering judgment and to consider site-specific environmental, traffic volume, traffic mix, geometric, and operational conditions which will affect the safety impact of a countermeasure. The user must ensure that a countermeasure applies to the particular conditions being considered. The reader is also encouraged to obtain and review the original source documents for more detailed information, and to search databases such as the National Transportation Library (ntlsearch.bts.gov) for information that becomes available after the publication of this issue brief.

**Presentation of the Crash Reduction Factors**

In the Tables presented in this issue brief, the crash reduction estimates are provided in the following format:

\[
\text{CRF(standard error)}^{\text{REF}}
\]

The CRF is the value selected from the literature.

The standard error is given where available. The standard error is the standard deviation of the error in the estimate of the CRF. The true value of the CRF is unknown. The standard error provides a measure of the precision of the estimate of the true value of the CRF. A relatively small standard error indicates that a CRF is relatively precisely known. A relatively large standard error indicates that a CRF is not precisely known. The standard error may be used to estimate a confidence interval of the true value of the CRF. (An example of a confidence interval calculation is given below.)

The REF is the reference number for the source information.

As an example, the CRF for the countermeasure remove or relocate fixed objects outside of clear zone for all crashes is:

\[
38^{(10)}^{\text{REF}17}
\]

The following points should be noted:

- The CRF of 38 means that a 38% reduction in all crashes is expected after removing or relocating fixed objects outside of the clear zone.

- This CRF is bolded which means that a) a rigorous study methodology was used to estimate the CRF, and b) the standard error is relatively small. A CRF which is not bolded indicates that a less rigorous methodology (e.g. a simple before-after study) was used to estimate the CRF and/or the standard error is large compared with the CRF.

- The standard error for this CRF is 10. Using the standard error, it is possible to calculate the 95% confidence interval for the potential crash reduction that might be achieved by implementing the countermeasure. The 95% confidence interval is ±2 standard errors from the CRF. Therefore, the 95% confidence interval for removing or relocating fixed objects outside of the clear zone is between 18% and 58% (38 - 2×10 = 18%, and 38 + 2×10 = 58%).

- The reference number is 17 (Hovey and Chowdhury, as listed in the References at the end of this issue brief).
Using the Tables

The CRFs for roadway departure crashes and other non-intersection crashes are presented in six tables which summarize the available information. The Tables are:

Table 1: Barrier Countermeasures
Table 2: Bridge Countermeasures
Table 3: Geometric Countermeasures
Table 4: Median Countermeasures
Table 5: Roadside Countermeasures
Table 6: Signs/Markings/Operational Countermeasures

The following points should be noted:

- Where available, separate CRFs are provided for different crash severities. The crash severities are: all, fatal/injury, fatal, injury, or property damage only (PDO).

- Where available, road type information is provided.

- Where available, daily traffic volume (vehicles/day) is provided.

- Blank cells mean that no information is reported in the source document.

- For additional information, please visit the FHWA Office of Safety website (safety.fhwa.dot.gov).
**Legend**

CRF (standard error)\(^{REF}\)

CRF is a crash reduction factor, which is an estimate of the percentage reduction that might be expected after implementing a given countermeasure. A number in bold indicates a rigorous study methodology and a small standard error in the value of the CRF.

Standard error, where available, is the standard deviation of the error in the estimate of the CRF.

REF is the reference number for the source information.

Additional crash types identified in the Other Crashes column are:

- a: Sideswipe
- b: Night
- c: Right-angle
- d: Left-turn
- e: Wet pavement
- f: Overturn
- g: Pedestrian
- h: Right-turn
- i: Animal
- j: Parking
- k: Wet weather
- l: Head-on/sideswipe
- m: Snow
- n: Truck-related
- o: Speed related
- p: Pedestrian walking along the roadway only

---

**Table 1: Barrier Countermeasures**

<table>
<thead>
<tr>
<th>Countermeasure(s)</th>
<th>Crash Severity</th>
<th>Area Type</th>
<th>Road Type</th>
<th>All Crashes</th>
<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve guardrail</td>
<td>All</td>
<td></td>
<td></td>
<td>18(^{9})</td>
<td>32(^{9})</td>
<td>41(^{9})</td>
<td>23(^{9})</td>
<td>f 41(^{9})</td>
<td>f 27(^{9})</td>
<td>≤5,000/lane</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td></td>
<td>9(^{9})</td>
<td>26(^{9})</td>
<td>27(^{9})</td>
<td>18(^{9})</td>
<td></td>
<td>f 27(^{9})</td>
<td>&gt;5,000/lane</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td></td>
<td>50(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>i 80(^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury</td>
<td></td>
<td></td>
<td>35(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>i 91(^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>i 61(^{9})</td>
<td></td>
</tr>
<tr>
<td>Install animal fencing</td>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td>i 80(^{9})</td>
<td></td>
<td></td>
<td></td>
<td>i 91(^{9})</td>
<td></td>
</tr>
<tr>
<td>Install barrier (concrete) inside and outside curve</td>
<td>Fatal/Injury</td>
<td></td>
<td></td>
<td>39(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>i 61(^{9})</td>
<td></td>
</tr>
<tr>
<td>Install guardrail (as shield for rocks and posts)</td>
<td>All</td>
<td></td>
<td></td>
<td>14(^{9})</td>
<td>31(^{9})</td>
<td>100(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (as shield for trees)</td>
<td>Fatal</td>
<td></td>
<td></td>
<td>65(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury</td>
<td></td>
<td></td>
<td>51(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (at culvert)</td>
<td>All</td>
<td></td>
<td></td>
<td>27(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (at ditch)</td>
<td>Injury</td>
<td></td>
<td></td>
<td>26(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (at embankment)</td>
<td>All</td>
<td></td>
<td></td>
<td>7(31)(^{8})</td>
<td>44(10)(^{8})</td>
<td>42(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fatal</td>
<td></td>
<td></td>
<td>42(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury</td>
<td></td>
<td></td>
<td>47(5)(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (inside curves)</td>
<td>Fatal/Injury</td>
<td></td>
<td></td>
<td>28(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (outside curves)</td>
<td>Fatal/Injury</td>
<td></td>
<td></td>
<td>63(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Install impact attenuators</td>
<td>All</td>
<td></td>
<td></td>
<td>29(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>69(28)(^{9})</td>
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<tr>
<td></td>
<td>Fatal</td>
<td></td>
<td></td>
<td>75(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>69(10)(^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury</td>
<td></td>
<td></td>
<td>50(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46(30)(^{9})</td>
<td></td>
</tr>
<tr>
<td>Replace guardrail with a softer material (concrete→steel→wire)</td>
<td>Fatal/Injury</td>
<td></td>
<td></td>
<td>41(31)(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury</td>
<td></td>
<td></td>
<td>32(10)(^{9})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 (continued on page 5)
### Table 2: Bridge Countermeasures

<table>
<thead>
<tr>
<th>Countermeasure(s)</th>
<th>Crash Severity</th>
<th>Area Type</th>
<th>Road Type</th>
<th>All Crashes</th>
<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Install bridge lighting</td>
<td>All</td>
<td></td>
<td></td>
<td>59&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install delineators (on bridges)</td>
<td>All</td>
<td></td>
<td></td>
<td>43&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install guardrail (at bridge)</td>
<td>All</td>
<td></td>
<td></td>
<td>22&lt;sup&gt;2&lt;/sup&gt;</td>
<td>37&lt;sup&gt;2&lt;/sup&gt;</td>
<td>f 41&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td>f 32&lt;sup&gt;2&lt;/sup&gt;</td>
<td>k 50&lt;sup&gt;2&lt;/sup&gt;</td>
<td>&gt;5,000/lane</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td>Fatal</td>
<td>20&lt;sup&gt;2&lt;/sup&gt;</td>
<td>32&lt;sup&gt;2&lt;/sup&gt;</td>
<td>f 32&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td>Injury</td>
<td>90&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair bridge deck</td>
<td>All</td>
<td></td>
<td></td>
<td>14&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace bridge (general)</td>
<td>All</td>
<td></td>
<td></td>
<td>45&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace bridge (2-lane)</td>
<td>All</td>
<td></td>
<td></td>
<td>45&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upgrade bridge parapet</td>
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<td></td>
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### Table 3: Geometric Countermeasures

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<th>Road Type</th>
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<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
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Table 3 (continued on page 6)
### Table 3 (continued)
**Geometric Countermeasures**

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<th>Rear-end Crashes</th>
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Table 3 (continued on page 7)
### Table 3 (continued)

#### Geometric Countermeasures

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<td>2-lane</td>
<td>32&lt;sup&gt;d&lt;/sup&gt;</td>
<td>32&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Widen lane (initially less than 9 ft)</td>
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<td>Rural</td>
<td>2-lane</td>
<td>50&lt;sup&gt;c&lt;/sup&gt;</td>
<td>49&lt;sup&gt;c&lt;/sup&gt;</td>
<td>7&lt;sup&gt;c&lt;/sup&gt;</td>
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Table 3 (continued on page 8)
## Table 3 (continued)
**Geometric Countermeasures**

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<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
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<td>2-lane</td>
<td>-1(4)^f</td>
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<td>2-lane</td>
<td>4(2)^f</td>
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<td>2-lane</td>
<td>21(6)^f</td>
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<td>Widen shoulder (from 6 to &gt;9 ft)</td>
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<td>Rural</td>
<td>2-lane</td>
<td>18(3)^f</td>
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<td>Widen shoulder (initially less than 1 ft)</td>
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<td>Rural</td>
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## Table 4: Median Countermeasures

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<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
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<td>Urban</td>
<td>Multilane</td>
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<td>Urban</td>
<td>2-lane</td>
<td>39(10)^i</td>
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<td>2-lane</td>
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<td>c 54^c&gt;5,000/lane</td>
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Table 4 (continued on page 9)
### Table 4 (continued)
**Median Countermeasures**

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<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
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<tr>
<td>Install median barrier (cable)</td>
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<td>Install median barrier (concrete)</td>
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<td>Highway (3-lane)</td>
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<td>29 (11)</td>
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<td>Install median barrier (steel)</td>
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<td>Multilane divided</td>
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### Table 5: Roadside Countermeasures

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<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
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<td>Install snow fencing</td>
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<td>Remove poles by burying utility lines</td>
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<td>Remove obstacles on curves to improve sight distance</td>
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<td>Remove or relocate fixed objects outside of clear zone</td>
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<td>All</td>
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<td>&gt;5,000/lane</td>
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### Table 6: Sign/Marking/Operational Countermeasures

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<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
<th>Other Crashes</th>
<th>Daily Traffic Volume (vehicles/day)</th>
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<td>Implement sign corrections to MUTCD standards</td>
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<td>Local</td>
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<td>fatal/injury</td>
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<td>Install curve advance warning signs</td>
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Table 6 (continued on page 11)
### Table 6 (continued)
#### Sign/Marking/Operational Countermeasures

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**Table 6 (continued)**  
**Sign/Marking/Operational Countermeasures**

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*Toolbox of Countermeasures and Their Potential Effectiveness for Roadway Departure Crashes*
### Table 6 (continued)
**Sign/Marking/Operational Countermeasures**

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<th>Road Type</th>
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<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
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<td>Reconfigure lanes within existing pavement width (two to three in one direction)</td>
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Table 6 (continued on page 14)
**Table 6 (continued)**
**Sign/Marking/Operational Countermeasures**

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<th>Road Type</th>
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<th>Run-off-Road Crashes</th>
<th>Head-on Crashes</th>
<th>Rear-end Crashes</th>
<th>Fixed Object Crashes</th>
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<th>Daily Traffic Volume (vehicles/day)</th>
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<td>Freeway</td>
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<td>Freeway</td>
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**References**

References (continued)


Session 3X: Exercise
TWO-LANE RURAL Highway

Part I:
From the Route 468 information, perform the following:

1. Predict the Crash Performance for the following:
   a. SPF Base Model for Route 468:

   \[ N_{spf-rs} = (ADT_n) (L_{total}) (365) (10^{-6}) e^{-0.312} \]

   \[ = (10,250)*(316/5280)*(365)(10^{-6}) e^{-0.312} \]

   \[ = 0.164 \text{ crashes per year} \]

   b. SPF Base Model with AMF’s for Lane Width, Shoulder Width, Hazard Rating, Access Density (Straight and Level)

   \[ AMF_r \text{ for Lane Width from Exhibit 10-14:} 1.05 \]

   \[ AMF_{1r} = (AMF_r -1.0)p_{ra} + 1.0 = 1.029 \]

   \[ AMF_{wra} \text{ for Shoulder Width from Exhibit 10-16:} 1.50 \]

   \[ AMF_{tra} \text{ for Shoulder Type from Exhibit 10-18:} 1.00 \]

   \[ AMF_{2r} = (AMF_{wra}xAMF_{tra}-1.0)p_{ra}+1.0 = 1.287 \]

   \[ N_{predicted-rs} = N_{spf-rs} x AMF_{1r} x AMF_{2r} \]

   \[ = 0.164 x 1.029 x 1.287 \]

   \[ = 0.217 \text{ crashes per year} \]
Part II:
From the Route 468 information for a horizontal curve of length = 316/5280, with radius of 600 feet and no spiral transition with super elevation in conformance with the AASHTO Policy on Geometric Design, perform the following:

2. Compute the Weighted AMF for the horizontal curve

b. \[ AMF_{\text{curve}} = \frac{1.55 \times L_c + \frac{80.2}{R} - 0.012 \times s}{1.55L_c} \]
   
   \[ = \frac{(1.55 \times \frac{316}{5280} + \frac{80.2}{600} - 0.012 \times 0)}{1.55 \times \frac{316}{5280}} \]
   
   \[ = \frac{2.441}{1.55} \]
   
   \[ = 2.441 \]

c. Compute the prediction of crashes for the Horizontal Curve

\[ N_{\text{curve}} = N_{\text{predicted-rs}} \times AMF_{\text{curve}} \]

\[ = 0.217 \times 2.441 \]

\[ = 0.53 \text{ crashes per year} \]