Speed Harmonization - Design Speed vs. Operating Speed

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- Mr. Jeff Blue, Mr. Brian Davis, Mr. Brian Wright, Mr. Tom Casson for providing helpful information during the interviews.
Introduction

- Good geometric design
  - appropriate mobility and land use access
  - high degree of safety

- Balance between mobility/accessibility and safety is often reflected by the “allowed” vehicle speed

- The design speed was used to determine the various geometric design features of a roadway.
  - critical for choosing super-elevation rates and radii of curves, sight distance, and the lengths of crest and sag vertical curves
  - Important for clean zone and guardrail design
Introduction

- Design speed often based on traffic volume and roadway functional classification
  - Potential discrepancy with the actual operating speed.
  - Anticipated operating speed – often used as design speed – may be lower than actual operating speed

Roadway design-class flow chart (Fitzpatrick et al. 2003)
**Introduction**

- The **operating speed** of a road is the speed at which vehicles generally operate on that road -- "the speed at which drivers are observed operating their vehicles during free-flow conditions."
  - The 85th percentile of the observed speeds is the most frequently used measure of the operating speed.
- A survey conducted by Schroeder et al. (2013)
  - 9.8% of the interviewees drive often or at least sometimes 15 mph over speed limit on two-lane highways
  - 19.1% of the participants admitted to driving 15 mph higher than the posted speed limit on multi-lane highways.
Problem Statement

- Most ironically, the design speed often does not have a direct relationship with the operating speed (except for the extreme case of a very sharp roadway curve).

Design speed versus observed operating speed: (a) rural two-lane highway; (b) suburban arterial (Fitzpatrick et al. 2003).
Summary

Methodology & software that

- Simulate acceptable geometric design
- Predict distribution of operating speed
- Predict crash rate
- Identify and assess safety improving countermeasures based on economic analysis
- Output: Design consistency level, crash rates, countermeasure recommendation
Literature Review

- Empirical relationships among design speed, posted speed limit and operating speed.
- Factors used to select the design speed.
- Possible strategies to narrow the discrepancy between design speed and operating speed.
- Operating speed prediction models
- Characteristics that influence the roadway safety
- Design consistency evaluation criteria
Interview with IDOT engineers

<table>
<thead>
<tr>
<th>Date</th>
<th>Department</th>
<th>Representative</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-Mar-16</td>
<td>Champaign County Highway Department</td>
<td>Mr. Jeff Blue</td>
<td>County Engineer</td>
</tr>
<tr>
<td>5-Apr-16</td>
<td>Sangamon County Highway Department</td>
<td>Mr. Brian Davis</td>
<td>Asst. County Engineer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mr. Brian Wright</td>
<td>Planning Engineer</td>
</tr>
<tr>
<td>7-Apr-16</td>
<td>Menard County Highway Department</td>
<td>Mr. Tom Casson</td>
<td>County Engineer</td>
</tr>
</tbody>
</table>

Brief Summary of the Questions

- Roadway Geometric Design
e.g. front slope (Q2), guardrail (Q3), clear zone (Q7, Q8, Q9).
- Design Speed, Operating Speed and Posted Speed Limit
e.g. design speed and operating speed (Q14, Q16, Q18, Q19), posted speed limit (Q12, Q15).
- Safety and Improvements
e.g. safety level (Q22), improvements (Q21, Q23).
Selected Questions and Answers

Existence of Disparities between Design Speed and Operating Speed

19. On two lane rural highway alignments, is there empirical evidence of disparities between design speeds and operating speeds?

- Champaign County Highway Department Response: Yes, the operating speed may be 5-10 mph greater.
- Sangamon County Highway Department Response: Based on our experience, the answer should be yes.
- Menard County Highway Department Response: Yes, the operating speed is larger than design speed and the statutory speed limits.
Selected Questions and Answers

Design Speed on Low Volume Roads

14. What is your Agency’s policy regarding the use of the design speed for the design of low volume roads when you know the operating speeds are much higher?

- **Champaign County Highway Department Response:**
  1. Operating speed is not included in design.
  2. Balance between safety and the cost.

- **Sangamon County Highway Department Response:**
  1. Design on speeds that are close to the posted speed limits.
  2. Post a lower speed limit.

- **Menard County Highway Department Response:**
  1. Cost is a very important factor.
  2. The ADT is very low, which is safer for drivers.
Summary of Interviews

Selected Questions and Answers

The Selection of Design Speed

18. What method is used by your Agency to determine the design speed? Does it give even a minor consideration to the operating speed?

Champaign County Highway Department Response:
The functional classification in Bureau of Local Roads and Streets Manual (BLRS) should be used.

Sangamon County Highway Department Response:
The Bureau of Local Roads and Streets Manual (BLRS) is used. It doesn’t consider operating speed.

Menard County Highway Department Response:
The Bureau of Local Roads and Streets Manual (BLRS) is used.
Summary of Interviews

- Is Clear Zone Sufficient?

8. What is your opinion regarding the clear zone requirements for culverts on a low volume, high operating speed roadway? Do you think a 6 or 7-foot clear zone policy is sufficient for these types of roadways?

**Champaign County Highway Department Response:**
For new projects: may not be sufficient.
For maintenance projects: too costly to widen the clear zone.

**Sangamon County Highway Department Response:**
Follow the Bureau of Local Roads and Streets Manual (BLRS) rules.

**Menard County Highway Department Response:**
May not be sufficient, but we are unable to extend it without enough right of way.
Summary of Interviews

Selected Questions and Answers

Safety and Improvements

23. What would you recommend to improve the safety level?

Champaign County Highway Department Response:
1. Removing fixed objects to reduce fatalities.
2. Proper signage.
3. Proper maintenance.

Sangamon County Highway Department Response:
1. Speed enforcement.
2. Zero tolerance of alcohol.

Menard County Highway Department Response:
Adding the advisory speed on curves and adding chevrons.
Challenges

- Discrepancy between design speed and operating speed is potentially problematic from a safety point of view.
  - Check consistency level between design speed and operating speed. Reduce crash rates using countermeasures.
- Safety features of geometric design (such as clear zone and guardrail length of need) are determined based on the lower design speed rather than the actual operating speed.
  - Determine whether higher design speed is appropriate through interview and simulation.
- No existing framework could evaluate both the safety and benefit/cost for different countermeasures
  - Incorporate economic analysis into the framework
Methodology

For existing/new site of interest

- Step 1: Simulate acceptable geometric design
- Step 2: Predict distribution of operating speed
- Step 3: Predict crash rate
- Step 4: If crash rate is large, identify and assess safety improving countermeasures based on economic analysis

Output: Design consistency level, crash rates, countermeasure recommendation
Step 1: Simulate Acceptable Geometric Design

- Design Guides

A Policy on Geometric Design of Highways and Streets

Bureau of Local Roads and Streets Manual

Illinois Department of Transportation
Division of Highways
Example

An Illustrative Example

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>Absolute value of the difference in grades $</td>
</tr>
<tr>
<td>V</td>
<td>50mph</td>
<td>Design speed</td>
</tr>
<tr>
<td>G1</td>
<td>-1</td>
<td>First grade in the direction of travel</td>
</tr>
<tr>
<td>G2</td>
<td>1</td>
<td>Second grade in the direction of travel</td>
</tr>
<tr>
<td>L₀</td>
<td>262ft</td>
<td>Horizontal distance between the point of vertical intersection and the point of horizontal intersection</td>
</tr>
<tr>
<td>AADT</td>
<td>1000vpd</td>
<td>Annual average daily traffic</td>
</tr>
<tr>
<td>LW</td>
<td>11ft</td>
<td>Lane Width</td>
</tr>
<tr>
<td>SW</td>
<td>5ft</td>
<td>Shoulder Width</td>
</tr>
<tr>
<td>Sag/Crest</td>
<td>Sag</td>
<td>Sag Vertical Curve</td>
</tr>
</tbody>
</table>
Example

- **Simulate Acceptable Designs**

  Given the absolute value of algebraic difference, design speed, AADT and other inputs, the following will be conducted:
  
  - **Step 1.** Calculate stopping sight distance.
  
  - **Step 2.** Check acceptable range of vertical curve length.
  
  - **Step 3.** Check acceptable range of curve radius and super-elevation rate.

  Applying the method to our example to get a range of acceptable designs.

\[
d = 1.47Vt + \frac{V^2}{30(\frac{a}{32.2} \pm G)}
\]

\[
R_v = \frac{V^2}{g(f_s + \frac{e}{100})}
\]

\[
e = \text{rate of roadway superelevation, per}
\]

\[
g = \text{gravitational constant, 32.2ft/s}^2
\]

\[
f_s = \text{coefficient of side friction (unitless)}
\]

\[
V = \text{design speed (ft/s)}
\]

\[
R_v = \text{radius defined to the vehicle's trave}
\]

For \( SSD < L \),

\[
L_m = \frac{A \cdot SSD^2}{200(H+S \cdot \tan \beta)^2}
\]

For \( SSD > L \),

\[
L_m = 2S - \frac{200(H+SSD \cdot \tan \beta)}{A}
\]

- \( H = \text{height of headlight in ft (m)} \)
- \( \beta = \text{inclined angle of headlight beam in degree} \)
- \( L_m = \text{minimum length of vertical curve in ft} \)
- \( A = \text{absolute value of the difference in grades } |G_1 - G_2| \)
Step 2: Predict Distribution of Operating Speed

- General roadway profile may include curves and tangent segments
- Speed varies on tangents and horizontal curves (Ottesen et al., 2000; Lamm et al., 1992; de Oña et al., 2013; Camacho-Torregrosa et al., 2013)

Figure: Speed profile (Source: Castro et al., 2008)
Step 2: Predict Distribution of Operating Speed

- 3D horizontal and vertical curves (Gibreel et al., 2001)

\[
\begin{align*}
V_{S1} &= 91.81 + 0.010r + 0.468\sqrt{L_V} - 0.006G_1^3 - 0.878\ln(A) - 0.826\ln(L_0) \\
V_{S2} &= 47.96 + 7.217\ln(r) + 1.534\ln(L_V) - 0.258G_1 - 0.653A - 0.008L_0 + 0.020\exp(e) \\
V_{S3} &= 76.42 + 0.023r + 2.300\times10^{-4}K^2 - 0.008\exp(A) - 1.230\times10^{-4}L_0^2 + 0.062\exp(e) \\
V_{S4} &= 82.78 + 0.011r + 2.067\ln(K) - 0.361G_2 + 0.036\exp(e) - 1.091\times10^{-4}L_0^2 \\
V_{S5} &= 109.45 - 1.257G_2 - 1.586\ln(L_0)
\end{align*}
\]

\(V_{S1}\) to \(V_{S5}\) = predicted 85th percentile operating speed at point 1 to point 5 (km/h).

- \(r\) = radius of horizontal curve (m),
- \(L_V\) = length of vertical curve (m),
- \(e\) = superelevation rate (percent),
- \(A\) = algebraic difference in grades (percent),
- \(K\) = rate of vertical curvature (m),
- \(G_1\) and \(G_2\) = first and second grades in the direction of travel in percent,
- \(L_0\) = horizontal distance between point of vertical intersection and point of horizontal intersection (m)
Step 2: Predict Distribution of Operating Speed

☐ Tangent Segments

\[ V_{85T} = V_{85C} + (1 - e^{-\lambda L}) \cdot (V_{des} - V_{85C}) \]

- \( V_{des} \) = desired speed (km/h), assumed 110 km/h from the literature;
- \( V_{85C} \) = 85th percentile speed on previous curves obtained from the proposed model;
- \( L \) = tangent length (m);
- \( R \) = curve radius (m);
- \( \lambda = 0.00135 + (R - 100) \cdot 7.00625 \cdot 10^{-6} \)
Example

- Simulate and normalize the probability distribution of speed at each location.
- Compute the mean and standard deviation.

\[
\begin{align*}
    v_j &= \int_{-\infty}^{+\infty} v f_j(v) dv \\
    SD_j &= \sqrt{\int_{-\infty}^{+\infty} (v - v_j)^2 f_j(v) dv}
\end{align*}
\]

\(j = \text{index of location. (1 to 5)}\)

\(f_j(v) = \text{normalized probability of density function at location } j\)

\(v_j = \text{mean of predicted operating speed at location } j\)

\(SD_j = \text{standard deviation of predicted operating speed at location } j\)

Result for the example
Evaluate Design Consistency

- **Criterion 1**: Difference between design speed and operating speed
- **Criterion 2**: Difference in operating speed on successive elements of the road
- **Criterion 3**: Driving dynamics (sufficient side friction)

<table>
<thead>
<tr>
<th>Consistency Level</th>
<th>Criterion 1 (km/h)</th>
<th>Criterion 2 (km/h)</th>
<th>Criterion 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>$</td>
<td>V_{85} - V_d</td>
<td>\leq 10$</td>
</tr>
<tr>
<td>Fair</td>
<td>$10 &lt;</td>
<td>V_{85} - V_d</td>
<td>\leq 20$</td>
</tr>
<tr>
<td>Poor</td>
<td>$</td>
<td>V_{85} - V_d</td>
<td>&gt; 20$</td>
</tr>
</tbody>
</table>

In the table, $V_{85}$ is the operating speed, $V_d$ is the design speed, $V_{85k}$ and $V_{85k+1}$ are the operating speeds on consecutive road sections $k$ and $k+1$. Parameters $f_R$ and $f_{RD}$ are respectively the assumed and demanded side frictions on a section.
Step 3: Predict Crash Rate

- Safety performance functions (SPFs)
  - Descriptive statistical relationships between crash counts and contributing factors (e.g., traffic volume)

- SPFs helps predict crash occurrence for any given geometric design and traffic exposure
Step 3: Predict Crash Rate

Crash rate on curves (Garber and Ehrhart, 2000)

Model 1: \( \ln(\text{crash rate}) = 44.323 - 25755.82/SD^2 + 93793.11/SD^4 - 8.686 \times 10^{-3} \times FPL^2 + 0.106/SD^2 \times FPL^2 - 1.68710^{-8} \times FPL^4 + 469.071/LW^{0.5} + 44529.25/SD^2/LW^{0.5} + (1.445 \times 10^{-2} \times FPL^2/LW^{0.5} - 956.114/LW^{0.5})^2 - 93.415 \times SW - 660.808/SD^2 \times SW + 5.626 \times 10^{-5} \times FPL^2 \times SW + 152.084/LW^{0.5} \times SW + 3.475 \times SW^2, R^2 = 0.9864, AIC = -48.715 \)

Model 2: \( 1/\text{crash rate}^{0.5} = 1132.667 - 3035.839/SD - 13380.54/SD^2 - 1.436 \times 10^{-3} \times FPL^2 - 4.313 \times 10^{-2}/SD \times FPL^2 + 1.752 \times 10^{-7} \times FPL^4 - 9519309/MEAN^2 - 6956803/SD/MEAN^2 - 71.254 \times FPL^2/MEAN^2 - 1.060174 \times 10^9/MEAN + 210.998 \times LW + 1963.584/SD \times LW + 3.751 \times 10^{-3} \times FPL^2 \times LW + 3334646/MEAN^2 \times LW - 65.918 \times LW^2, R^2 = 0.9817, AIC = 18.247 \)

Model 3: \( 1/\text{crash rate}^{0.5} = 23635.61 - 17107.41/SD - 12605.73/SD^2 - 1.184 \times FPL - 10.318/SD \times FPL + 2.621 \times 10^{-3} \times FPL^2 - 25345.75/LW^{0.5} + 10829.1/SD \times LW^{0.5} + 1.051 \times FPL \times LW^{0.5} + 6744.683/LW \times 156.286 \times SW^{2} + 199.0262/SD \times SW^2 - 8.073 \times 10^{2} \times FPL \times SW^2 + 89.694 \times LW^{0.5} \times SW^{2} - 2.945 \times SW^4, R^2 = 0.9697, AIC = 28.845 \)

Model 4: \( 1/\text{crash rate} = 1331486 - 1365.183/SD - 5.771 \times SD^2 - 0.541 \times FPL^2 + 6.709 \times 10^{-3} \times SD \times FPL^2 + 3.204 \times 10^{-6} \times FPL^4 - 4744279/LW^{0.5} + 2739.721/SD \times LW^{0.5} + 0.873 \times FPL^2/LW^{0.5} + 4219166/LW + 1871.932 \times SW^2 - 23.51972/SD \times SW^2 - 0.031 \times FPL^2 \times SW^2 - 2230.496/LW^{0.5} \times SW^2 - 47.560/SD^{2 \times SW^2}, R^2 = 0.9312, AIC = 171.06 \)

**Notation**

AIC = Akaike’s information criterion
FPL = flow per lane (vph)
LW = lane width (m)
MEAN = the mean speed (km/h)
\( R^2 \) = coefficient of determination
SD = standard deviation of speed (km/h)
SW = shoulder width (m)
Step 3: Predict Crash Rate

- Crash Rates on Tangent (Camacho-Torregrosa et al., 2013)

\[
ECR = \frac{1}{2.40939 + 0.00403287 \times (\bar{\nu}_{85}^2 / \Delta \bar{\nu}_{85})}
\]

Where

- \( ECR \) = estimated crash rates (crashes/10^6 vehicles - km/10 years)
- \( \bar{\nu}_{85} \) = Average operating speed
- \( \Delta \bar{\nu}_{85} \) = Average speed reduction, the average value of all speed reduction processes at each road segment.

Result for the example

| \( \bar{\nu}_{85} \) (mile/h) | 62.6 |
| \( \Delta \bar{\nu}_{85} \) (mile/h) | 2.031 |
| \( ECR \) * (crash/10^6 veh-mile) | 0.1078 |

*Will be adjusted by shoulder width and lane width
Step 4: Identify and Assess Countermeasures

Possible strategies to reduce the discrepancy between design speed and operating speed

- Change design speed (European countries and Australia)
  1. Design a preliminary alignment based on a given design speed
  2. Estimate the operating speeds (85th percentile speeds)
  3. Check the difference on successive curves.
  4. Revise the geometric alignment to narrow the gap to acceptable levels.

- Improve roadway design (recommended)
  - Identify relevant design features
  - Use Crash Modification Factors adjust the base predictions according to the changed roadway features
Step 4: Identify and Assess Countermeasures

- Geometric Characteristics that Influence Safety

  **Lane Width.**
  Garber et al. (1993) showed that larger lane width could improve safety. However, several researchers did not observe such a relationship (Dart and Mann, 1970). Noland et al. (2004) found that lane widths appear to be associated with increased fatalities.

  **Shoulder Width.**
  Raff (1953), Perkins (1956) and Noland et al. (2004) claimed that larger shoulder width could reduce the crash rates; Cirillo et al. (1969) did not observe such a relationship.

  **Degree of curvature.**
  Fink et al. (1995) showed that crash rate increases almost linearly with degree of curvature.
Step 4: Identify and Assess Countermeasures

Crash Modification Factors for Shoulder Width

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

- \( CMF_{2r} \) = crash modification factor for the effect of shoulder width and type on total crashes;

- \( CMF_{wra} \) = crash modification factor for related crashes (i.e., single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes), based on shoulder width;

- \( CMF_{tra} \) = crash modification factor for related crashes based on shoulder type;

- \( p_{ra} \) = proportion of total crashes constituted by related crashes. (Illinois default value=0.372)
Step 4: Identify and Assess Countermeasures

- Crash Modification Factors for Lane Width

<table>
<thead>
<tr>
<th>Lane Width</th>
<th>AADT (vehicles per day)</th>
<th>&lt; 400</th>
<th>400 to 2000</th>
<th>&gt; 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 ft or less</td>
<td></td>
<td>1.05</td>
<td>1.05 + 2.81 \times 10^{-4} (AADT – 400)</td>
<td>1.50</td>
</tr>
<tr>
<td>10 ft</td>
<td></td>
<td>1.02</td>
<td>1.02 + 1.75 \times 10^{-4} (AADT – 400)</td>
<td>1.30</td>
</tr>
<tr>
<td>11 ft</td>
<td></td>
<td>1.01</td>
<td>1.01 + 2.5 \times 10^{-5} (AADT – 400)</td>
<td>1.05</td>
</tr>
<tr>
<td>12 ft or more</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note: The collision types related to lane width to which this CMF applies include single-vehicle run-off-the-road and multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe crashes.
Example

Safety Impacts of Widening Shoulder

Estimated Crash Rates vs. Shoulder Width

![Graph showing estimated crash rates vs. change in shoulder width (ft)]
Step 4: Identify and Assess Countermeasures

- Benefit & Cost Analysis
  - Safety Benefit

  \[ b_i = C_a \cdot R_i \cdot AADT \cdot L \cdot ECR \cdot 365 \cdot \frac{(1 + s)^{n_i} - 1}{s(1 + s)^{n_i}}, \]

  where

  - \( b_i \) = present value of safety benefits of countermeasure \( i \) (\$)
  - \( C_a \) = average cost of each accident (\$)
  - \( R_i \) = CRF (crash reduction factor) value for countermeasure \( i \), which is the expected percent decrease in crash rates due to countermeasure implementation. Calculated as \((1 - CMF)\),
  - \( AADT \) = average annual daily traffic (vehicles/day)
  - \( ECR \) = estimated crash rates (crashes/10^6 vehicles -mile)
  - \( L \) = roadway segment length (mile)
  - \( s \) = minimum attractive rate of return expressed as a decimal fraction
  - \( n_i \) = service life of countermeasure \( i \)
Example

- Benefit & Cost Analysis
  - Cost
    \[ c_i = C_i \cdot \Delta x_i, \]
    where \( c_i \) = cost of countermeasure \( i \) (dollars),
    \( C_i \) = unit cost of countermeasure \( i \) (dollars/unit),
    \( \Delta x_i \) = units of improvement of countermeasure \( i \).
  - Countermeasure Selection
    \[
    \text{maximize} \sum_{i \in I} b_i \cdot x_i,
    \]
    \[
    \text{s.t.} \sum_{i \in I} c_i x_i \leq D,
    \]
    \[
    x_i \in \{0, 1\}, \forall i \in I.
    \]
    where \( x_i \) = decision variable for countermeasure \( i \),
    \( b_i \) = present value of safety benefits of countermeasure \( i \),
    \( c_i \) = cost of countermeasure \( i \),
    \( D \) = agency’s budget,
    \( I \) = set of countermeasure candidates.

0-1 Knapsack Problem: Can be solved using dynamic programming methods.
Example

Countermeasure Evaluation

Consider a 5-mile roadway section, and three countermeasure candidates including:
(1) widening shoulder width from 5ft to 6ft,
(2) widening lane width from 11ft to 12ft, and
(3) installing advisory speed sign (assuming there is no speed sign installed initially).

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash</td>
<td>1,565,439 $/crash</td>
<td>IDOT</td>
</tr>
<tr>
<td>Shoulder Widening</td>
<td>4.33$/ft²</td>
<td>Illinois Data</td>
</tr>
<tr>
<td>Lane Widening</td>
<td>4.44$/ft²</td>
<td>Ohio Data</td>
</tr>
<tr>
<td>Advisory Speed Sign</td>
<td>2000$</td>
<td>Internet</td>
</tr>
<tr>
<td>Budget</td>
<td>150,000$</td>
<td></td>
</tr>
</tbody>
</table>
Example

- Benefit & Cost Analysis (shoulder width)

![Graph showing Benefit Cost Ratio vs. Shoulder Width](image_url)

- Benefit Cost Ratio vs. Shoulder Width

<table>
<thead>
<tr>
<th>Change of Shoulder Width (ft)</th>
<th>BCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.37</td>
</tr>
<tr>
<td>1</td>
<td>0.38</td>
</tr>
<tr>
<td>1.5</td>
<td>0.39</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>2.5</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
</tr>
<tr>
<td>3.5</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Example

- Countermeasure Evaluation

<table>
<thead>
<tr>
<th>Countermeasure</th>
<th>Benefit $b_i$/</th>
<th>Cost $c_i$/</th>
<th>Life cycle/y</th>
<th>$BCR_i$</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widening shoulder width from 5ft to 6ft</td>
<td>53224</td>
<td>113653</td>
<td>20</td>
<td>0.47</td>
<td>Not to select</td>
</tr>
<tr>
<td>Widening lane width from 11ft to 12ft</td>
<td>83244</td>
<td>116541</td>
<td>20</td>
<td>0.75</td>
<td>Select</td>
</tr>
<tr>
<td>Installing advisory speed sign</td>
<td>177245</td>
<td>2000</td>
<td>5</td>
<td>88.6</td>
<td>Select</td>
</tr>
</tbody>
</table>

\[
\text{maximize } \sum_{i \in I} b_i \cdot x_i, \\
\text{s.t. } \sum_{i \in I} c_i x_i \leq D, \\
x_i \in \{0, 1\}, \forall i \in I.
\]

Using Countermeasure 2 & 3
0.1092 crashes/10^6veh-mile
→ 0.0938 crashes/10^6veh-mile

Crash Rates Reduced
Case Study: Clear Zone and Guardrail

- Hypothetical 5-mile roadway section
  - 4-ft paved shoulder, 12-ft clear zone, no guardrail (cost= $39/ft), ADT = 1000 vehicles
  - Other geometric elements and costs remain the same

- Countermeasures
  Case 1: 12-ft clear zone, 4-ft shoulder (benchmark)
  Case 2: 16-ft clear zone, 6-ft shoulder
  Case 3: 20-ft clear zone, 8-ft shoulder
  Case 4: Installing guardrails (39$/ft)
  Case 5: Increasing design speed to 60 mph (~ operating speed), 20-ft clear zone, 8-ft shoulder

<table>
<thead>
<tr>
<th>Case</th>
<th>CMF</th>
<th>Crash Rate (Crashes/10^6 mile-veh)</th>
<th>Benefit $</th>
<th>Cost $</th>
<th>Benefit/Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.026</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.107</td>
<td>106,448</td>
<td>227,308</td>
<td>0.468</td>
</tr>
<tr>
<td>3</td>
<td>0.977</td>
<td>0.105</td>
<td>201,284</td>
<td>454,615</td>
<td>0.443</td>
</tr>
<tr>
<td>4</td>
<td>0.93</td>
<td>0.997</td>
<td>397,803</td>
<td>1,029,600</td>
<td>0.389</td>
</tr>
<tr>
<td>5</td>
<td>0.977</td>
<td>0.11</td>
<td>0</td>
<td>&gt; 454,615</td>
<td>0</td>
</tr>
</tbody>
</table>
Software Development

- Excel VBA with GUI

**Safety and Economic Analysis Tool for Roadway Geometric Design**

*This Safety and Economic Analysis tool was developed for the Illinois Department of Transportation to check the roadway design consistency, evaluate safety impact of roadway geometric features and select appropriate safety countermeasures.*
Software Development

- User Interface for Input

[Image of software interface showing input fields for Design Speed, Crest/Sag, First Grade, Horizontal distance, Lane Width, Curve Radius, Length of Vertical Curve, and Superelevation Rate.]

[Image of software interface showing additional input fields for Enter Estimated Budget and a list of countermeasures: Widening Shoulder, Widening Lane, Installing Advisory Speed Sign, Installing Guardrail.]

[Buttons for Analysis Result, Recommendation, and Quit.]
Software Development

- Sample Output

![Sample Output Images]
Summary

Methodology & software that

- Simulate acceptable geometric design
- Predict distribution of operating speed
- Predict crash rate
- Identify and assess safety improving countermeasures based on economic analysis
- Output: Design consistency level, crash rates, countermeasure recommendation
Thank You!

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8. Do you maintain your Agency’s roads differently for roads with low volume and low operating speeds than with high operating speeds? (Low volume roads are considered as roads with a traffic volume of 400 vehicles per day or less).

Champaign County Highway Department Response:
Yes, there are 1600 miles of township roads and it is too expensive to maintain them as high speed roads.

Sangamon County Highway Department Response:
They are treated the same. No preference will be given to the roads based on ADT.

Menard County Highway Department Response:
Yes, county highways are maintained better than rural roads.
Factors used to select design speed (Source: Fitzpatrick et al., 2003)

<table>
<thead>
<tr>
<th>AASHTO Policy</th>
<th>State DOT Survey</th>
<th>International Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional classification</td>
<td>Functional classification</td>
<td>Anticipated operating speed</td>
</tr>
<tr>
<td>Rural versus urban</td>
<td>Legal speed limit</td>
<td>Feedback loop</td>
</tr>
<tr>
<td>Terrain type</td>
<td>Legal speed limit plus a value (e.g., 5 or 10 mph)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anticipated volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anticipated operating speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Terrain type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consistency</td>
<td></td>
</tr>
</tbody>
</table>

Some of these design procedures give little consideration to operating speed when selecting design speed. Such design may cause safety issues.
Predict Distribution of Operating Speed

- Operating Speed Prediction Model on Tangent
  - 2D Model (Zuriaga et al. 2010)
  
  1. Operating Speed Models on Curves
     \[ V_{85} = 97.4254 - 3310.94/r \]
     \[ V_{85} = 1/(0.00948323 + 0.0000136809 \times CCR) \]
     \[ V_{85} = 102.048 - 3990.26/r \]

  2. Operating Speed Models on Tangents
     \[ V_{85} = V_{85C} + (1 - e^{-\lambda L}) \cdot (V_{des} - V_{85C}) \]

  3. Deceleration Models
     \[ d_{85} = 0.263571 + 67.7999/r \]
     \[ d_{85} = 0.242186 + 0.00150693/r \]
     where \( CCR \) = curvature change rate (°/km)
     \[ V_{des} \] = desired speed (km/h)
     \[ V_{85C} \] = 85th percentile speed on previous curves obtained from the proposed model
     \[ L \] = tangent length (m)
     \[ r \] = curve radius
Step 3: Predict Crash Rate

- Speed characteristics
  - Actual speed
    
    relative risk = $e^{-0.822957835 - 0.083680149V + 0.001623269V^2}$
    where V=free travelling speed in km/h.

    \[ LO_2 = LO_1 \left( \frac{v_2}{v_1} \right)^2 \]
    
    $LO_1$ = initial number of injury crashes
    $LO_2$ = number of injury crashes after the change in speed
    $v_1$ = average speed before the change
    $v_2$ being the average speed afterwards.

  - Speed deviation
Example

- Predict Operating Speed on Curve
  - Step 3. Calculate the mean and standard deviation of operating speed at each location using the following equation. Apply the method to our case as well as several different design speeds, we could get the following result.

<table>
<thead>
<tr>
<th>Consistency Level</th>
<th>Criterion 1 (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>$</td>
</tr>
<tr>
<td>Fair</td>
<td>$10 &lt;</td>
</tr>
<tr>
<td>Poor</td>
<td>$</td>
</tr>
</tbody>
</table>
Example

- Predict Operating Speed on Curve

Using lower design speed could reduce operating speed. But large difference between design speed and operating speed, which is not preferable, could appear when design speed is relatively low.
Characteristics that Influence Roadway Safety

- Road Type

   Motorways have the lowest crash rate

   - Rural roads and, to an even larger extent, urban roads, have much more complex traffic environments.

   - Roadway design speed also has an influence.
     On a road with a design speed of 80 km/h, a speed increase from 80 to 90 km/h results in a larger increase in crash rate than the same increase on a road with a design speed of 100 km/h. This is a consequence of 80 km/h roads not being designed for these faster speeds.
Characteristics that Influence Roadway Safety

- Traffic characteristics (Martin et al. 2002)
Possible strategies to narrow the discrepancy between design speed and operating speed.

- Set the design speed at the anticipated posted or operating speed plus a preset incremental increase.

However, Fitzpatrick (2003) noticed that adding 5 or 10 mph to the speed limit could be insufficient in some rural areas. Also, it could result in different posted speed limits for roads in a similar functional class.
Propose a new framework including the following modules:

(i) geometric design simulation
(ii) operating speed profile prediction
(iii) crash rate prediction
(iv) benefit-and-cost analysis and countermeasure recommendation
Literature Review

□ Highway Safety Manual
  ■ Safety Performance Functions
    predicted number of total crashes for base conditions based on the crash history

\[ NBR = ADT \times L \times 10^{-6} \times e^{-0.4865} \]

Where,

\( NBR \) = predicted number of total highway element crashes per year;

\( ADT \) = average daily traffic volume (vehicle/day);

\( L \) = length of highway element (km).

■ Crash Modification Factors
  Adjust the base predictions to reflect the roadway features