CONTROLLING CREST VERTICAL CURVATURE RATES BASED ON VARIABLE GRADE STOPPING SIGHT DISTANCE CALCULATION

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Stopping Sight Distance (SSD)

- Highway Geometric Design Element of Fundamental Importance
  - must be provided at every point along the road surface
  - affects critical road design parameters (e.g. vertical curvature)
    - impose economic considerations on new road designs and road improvement projects
Grade Impact in SSD Calculation

- Based on AASHTO’s Design Guide (Green Book)
  - significant difference in SSD between upgrades and downgrades
  - regarding vertical curves, the grade effect is somewhat balanced and there is no need to adjust SSD due to grade

- Moreover, the Green Book states...
  - *the minimum lengths of crest vertical curves, based on sight distance criteria, generally are satisfactory from the standpoint of safety, comfort and appearance.*

  implying that the vertical curvature rate is adequately determined through the suggested control values
Objective

- Investigate the Sufficiency of the Suggested Crest Vertical Curvature Rates by AASHTO from the Grade Control Point of View
  - current definition is based on a level road surface
  - maximum grade values vary depending on the road’s functional classification
Current SSD Determination

SSD = \( V_0 \cdot t_{pr} + \frac{V_0^2}{2g(\frac{a}{g} + s)} \)

where:
- \( V_0 \) (m/sec) : vehicle initial speed
- \( t_{pr} \) (sec) : driver’s perception – reaction time [2.5sec; AASHTO, 2011]
- \( g \) (m/sec\(^2\)) : gravitational constant [9.81m/sec\(^2\) (32.2ft/sec\(^2\))] \( g \) (m/sec\(^2\)) : gravitational constant [9.81m/sec\(^2\) (32.2ft/sec\(^2\))]
- \( a \) (m/sec\(^2\)) : vehicle deceleration rate [3.4m/sec\(^2\) (11.2ft/sec\(^2\)); AASHTO, 2011]
- \( s \) (%/100) : road grade [(+) upgrades, (-) downgrades]
Current Crest Vertical Curvature Determination

\[ L = \frac{(s_2 - s_1)SSD^2}{200(\sqrt{h_1} + \sqrt{h_2})^2} \]  
\[ L = 2SSD - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{s_2 - s_1} \]

where:

- \( K \): vertical curvature rate (m)
- \( L \): length of vertical curve (m)
- \( SSD \): stopping sight distance (m)
- \( h_1 \): driver eye height (m) [1.08m (3.50ft); AASHTO 2011]
- \( h_2 \): object height (m) [0.60m (2.00ft); AASHTO 2011]
- \( s_1, s_2 \): grade values (%)
CVCR Calculation Approaches

- **2D Approach**
  - fragmented approach

- **In Current Practice, Grade Effect is Addressed through Various Considerations**
  - **RAA (2008)**
    - values used for the crest vertical curvature rate determination are reached for most unfavorable (negative) grade values
  - **OMOE-X (2001)**
    - +10km/h safety margin in the CVCR calculation
## AASHTO Design Control Values for SSD and Crest Vertical Curvature Rates (CVCR)

<table>
<thead>
<tr>
<th>Metric</th>
<th>US Customary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{design}$ (km/h)</td>
<td>SSD (m)</td>
</tr>
<tr>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>60</td>
<td>85</td>
</tr>
<tr>
<td>70</td>
<td>105</td>
</tr>
<tr>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>90</td>
<td>160</td>
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<tr>
<td>100</td>
<td>185</td>
</tr>
<tr>
<td>110</td>
<td>220</td>
</tr>
<tr>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>130</td>
<td>285</td>
</tr>
</tbody>
</table>
BRAKING CALCULATION ON VARIABLE GRADES (1/5)

- **Current Practice**
  - **constant grades**
    - balanced assumptions
      - mean grade value adopted
      - failure in delivering actual braking results (SSD<L)

- **variable grades**
  - balanced assumptions
    - mean grade value adopted
    - failure in delivering actual braking results (SSD<L)

\[
SSD = V_o t_{pr} + \frac{V_o^2}{2g} + \frac{g}{a}(s + \frac{g}{a})
\]
Suggested Approach

variable grade impact during braking

\[ V_{i+1} = V_i - g\left(\frac{a}{g} + s_i\right)t \]

\[ BD_i = V_i t - \frac{1}{2} g\left(\frac{a}{g} + s_i\right)t^2 \]

SSD = \( V_o t_{pr} + \sum BD_{k-1} \)

where:
- \( V_i \) (m/sec): vehicle speed at a specific station \( i \)
- \( V_{i+1} \) (m/sec): vehicle speed reduced by the deceleration rate for \( t = 0.01 \) sec
- \( t \) (sec): time fragment (\( t = 0.01 \) sec)
- \( s_i \) (%/100): road grade in \( i \) position [(+)] upgrades, (-) downgrades]
- \( BD_i \) (m): pure braking distance
- \( V_o \) (m/sec): vehicle initial speed
- \( \sum BD_{k-1} \) (m): total vehicle pure braking distance for the initial value of vehicle speed
BRAKING CALCULATION ON VARIABLE GRADES (3/5)

- $V_{\text{design}} = 70\text{ km/h (45 mph)}, \ SSD = 105\text{ m (360 ft)}, \ K = 17\text{ m (61 ft)}$
BRAKING CALCULATION ON VARIABLE GRADES (4/5)

- \( V_{\text{design}} = 70 \text{ km/h} (45 \text{ mph}) \), SSD = 105 m (360 ft), K = 17 m (61 ft)

CASE 1
- SSD = 96.3 m (316 ft)
- K = 17 m
- \( s_1 = 10\% \)
- \( s_2 = -10\% \)
- Dperc-reac = 48.6 m
- Dbreaking = 47.7 m

L = 340.00 m

St. 0.00

St. 170.00

St. 340.00
BRAKING CALCULATION ON VARIABLE GRADES (5/5)

- $V_{\text{design}} = 70 \text{ km/h (45 mph)}$, SSD $= 105 \text{ m (360 ft)}$, K $= 17 \text{ m (61 ft)}$
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{design} = 45\text{ mph} (70\text{ km/h})$
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{\text{design}} = 50 \text{ km/h} \ (30 \text{ mph})$
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{\text{design}} = 80 \text{ km/h} \ (50 \text{ mph})$
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{\text{design}} = 50\text{ mph} \ (80\text{ km/h})$
### Suggested CVCR

\[
V_{\text{design}} = 50_{\text{mph}} \left( 80_{\text{km/h}} \right)
\]

- **Road’s Functional Classification**
- **Exit Grade Value**

<table>
<thead>
<tr>
<th>Type of Terrain</th>
<th>AASHTO</th>
<th>Exit Grade Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-3</td>
</tr>
<tr>
<td><strong>Local Rural</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level</td>
<td></td>
<td>26m</td>
</tr>
<tr>
<td>Rolling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountainous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level</td>
<td></td>
<td>26m</td>
</tr>
<tr>
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<td></td>
</tr>
</tbody>
</table>

**Note:**
- Values are given in both metric units (m) and US customary units (ft).
- The table represents the suggested Values for various types of roads with different grades and lengths.
SUGGESTED CVCR

\[ V_{\text{design}} = 50 \text{ mph} \ (80 \text{ km/h}) \]

- **Road’s Functional Classification**
- **Exit Grade Value**

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<tr>
<th>Type of Terrain</th>
<th>AASHTO Level</th>
<th>Exit Grade Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Collectors</td>
<td>26m (L&gt;132m)</td>
<td>-3 27m (L&gt;136m) 28m (L&gt;134m) 29m (L&gt;139m) 30m (L&gt;142m) 31m (L&gt;144m) 32m (L&gt;147m) 33m (L&gt;151m) 34m (L&gt;155m) 35m (L&gt;159m)</td>
</tr>
<tr>
<td></td>
<td>84ft (L&gt;436ft)</td>
<td>-4 88ft (L&gt;443ft) 91ft (L&gt;451ft) 95ft (L&gt;459ft) 98ft (L&gt;468ft) 102ft (L&gt;478ft) 106ft (L&gt;488ft) 111ft (L&gt;498ft)</td>
</tr>
<tr>
<td>Urban Arterials</td>
<td>26m (L&gt;132m)</td>
<td>-5 27m (L&gt;136m) 28m (L&gt;134m) 29m (L&gt;139m) 30m (L&gt;142m) 31m (L&gt;144m) 32m (L&gt;147m) 33m (L&gt;151m) 34m (L&gt;155m) 35m (L&gt;159m)</td>
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<tr>
<td></td>
<td>84ft (L&gt;436ft)</td>
<td>-6 88ft (L&gt;443ft) 91ft (L&gt;451ft) 95ft (L&gt;459ft) 98ft (L&gt;468ft) 102ft (L&gt;478ft) 106ft (L&gt;488ft) 111ft (L&gt;498ft)</td>
</tr>
<tr>
<td>Freeways</td>
<td>26m (L&gt;132m)</td>
<td>-7 27m (L&gt;136m) 28m (L&gt;134m) 29m (L&gt;139m) 30m (L&gt;142m) 31m (L&gt;144m) 32m (L&gt;147m) 33m (L&gt;151m) 34m (L&gt;155m) 35m (L&gt;159m)</td>
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**Notes:**
- Metric units (m) vs. US customary units (ft)
- Urban and Mountainous terrains have different grading requirements.
Conclusions

- Consequence Investigation of Green Book Guidelines to Adopt Control CVCR based on Leveled Grade Values

- SSD Calculation on Variable Grades
  - point mass model, laws of mechanics
    - evaluate negative grade area of crest vertical curves
Conclusions

- **Wide Range of Design Speed Values**
  - amended CVCR
    - based on ending grade value
    - length of the vertical curve exceeds SSD

- **Ready-to-Use CVCR**
  - in accordance to roadway’s functional classification
Further Research

- Assess the Impact of Combined Horizontal – Vertical Alignment

- Additional Qualitative Research in Current Vehicle Dynamics Trends
  - evaluate parameters of SSD
    - braking on curves
    - ABS braking
    - friction coefficient etc.

- Human Factor might Impose Additional Restrictions

- Parameters Refer to Daylight Driving Conditions