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

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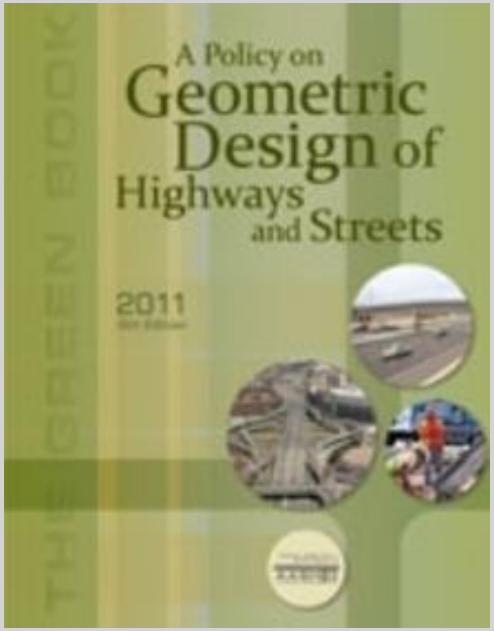
Stopping Sight Distance (SSD)

- 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

$$SSD = V_o t_{pr} + \frac{V_o^{\,2}}{2g(\frac{a}{g} + s)}$$

where :

V_o (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)]

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

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

SSD≤L

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

SSD>L

$$K = \frac{L}{s_2 - s_1}$$

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)

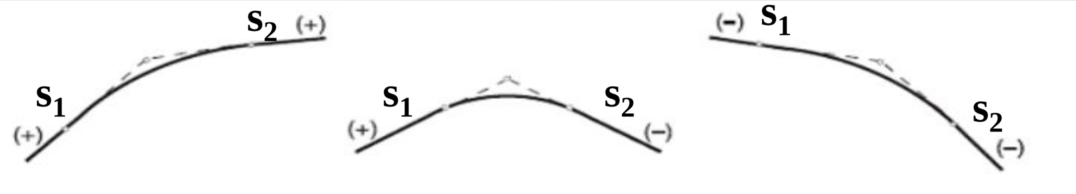
Metric			US Customary		
V_{design} (km/h)	SSD (m)	K (m)	V_{design} (mph)	SSD (ft)	K (ft)
50	65	7	30	200	19
60	85	11	40	305	44
70	105	17	45	360	61
80	130	26	50	425	84
90	160	39	55	495	114
100	185	52	60	570	151
110	220	74	70	730	247
120	250	95	75	820	312
130	285	124	80	910	384

BRAKING CALCULATION ON VARIABLE GRADES (1/5)

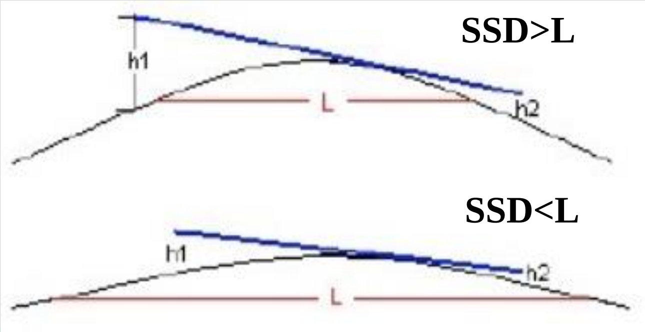
- Current Practice
  - constant grades

$$SSD = V_o t_{pr} + \frac{V_o^2}{2g\left(\frac{a}{g} + s\right)}$$

  - variable grades



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



BRAKING CALCULATION ON VARIABLE GRADES (2/5)

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 = 0.01sec

t (sec) : time fragment (t = 0.01sec)

s_i (%/100) : road grade in i position [(+) upgrades, (-) downgrades]

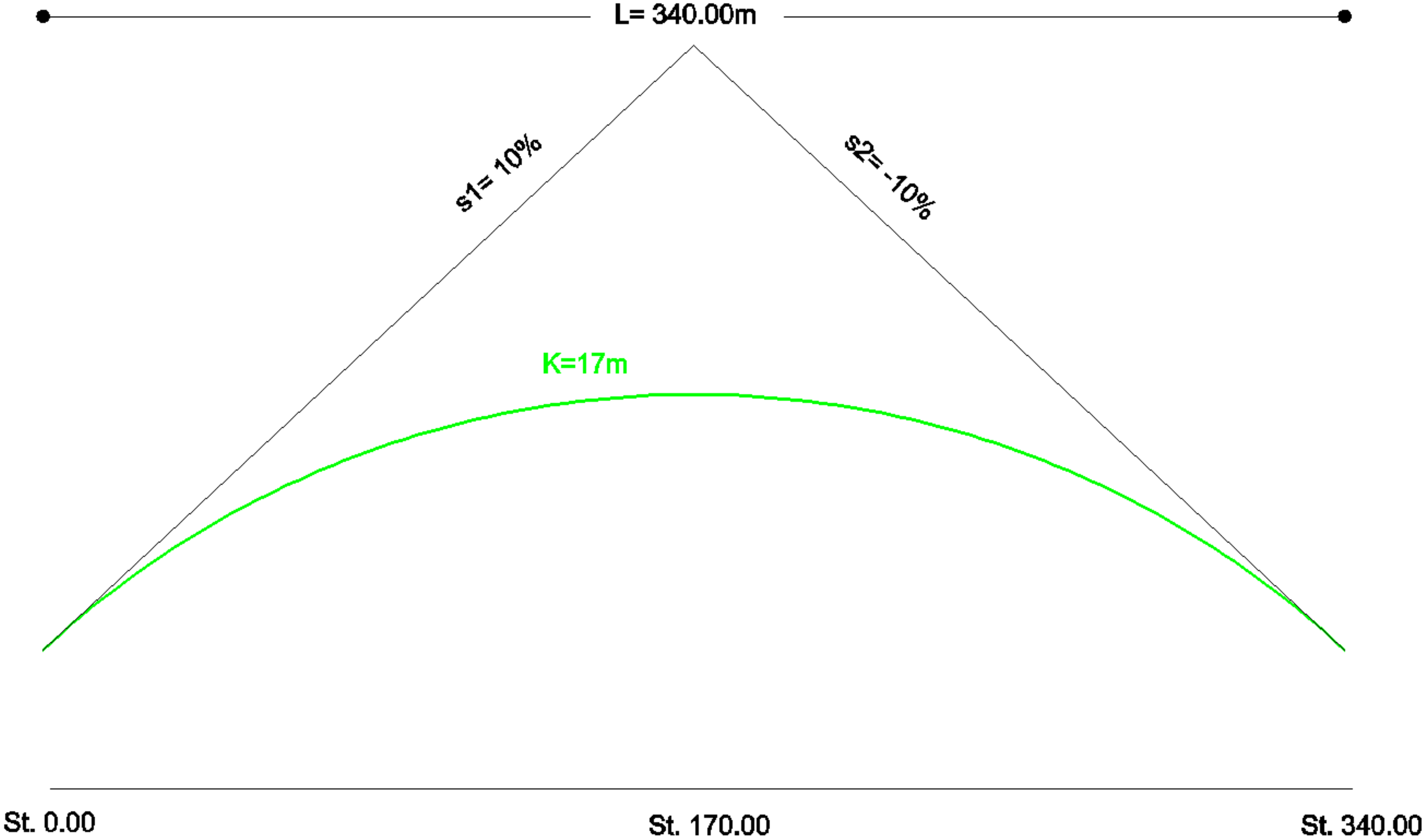
BD_i (m) : pure braking distance

V_o (m/sec) : vehicle initial speed

$\sum BD_{k-1}$ (m): total vehicle pure braking distance for the initial value of vehicle speed

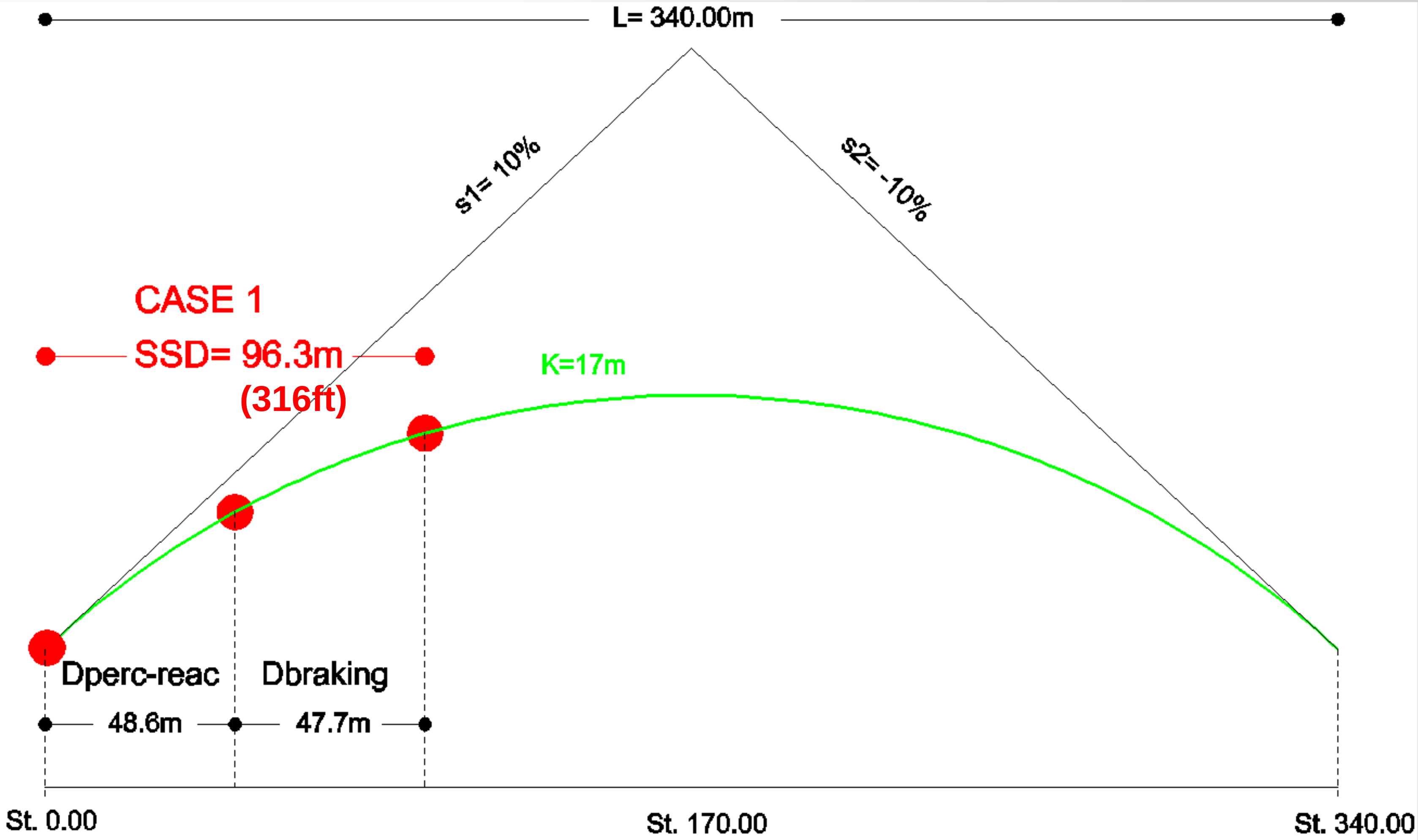
BRAKING CALCULATION ON VARIABLE GRADES (3/5)

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



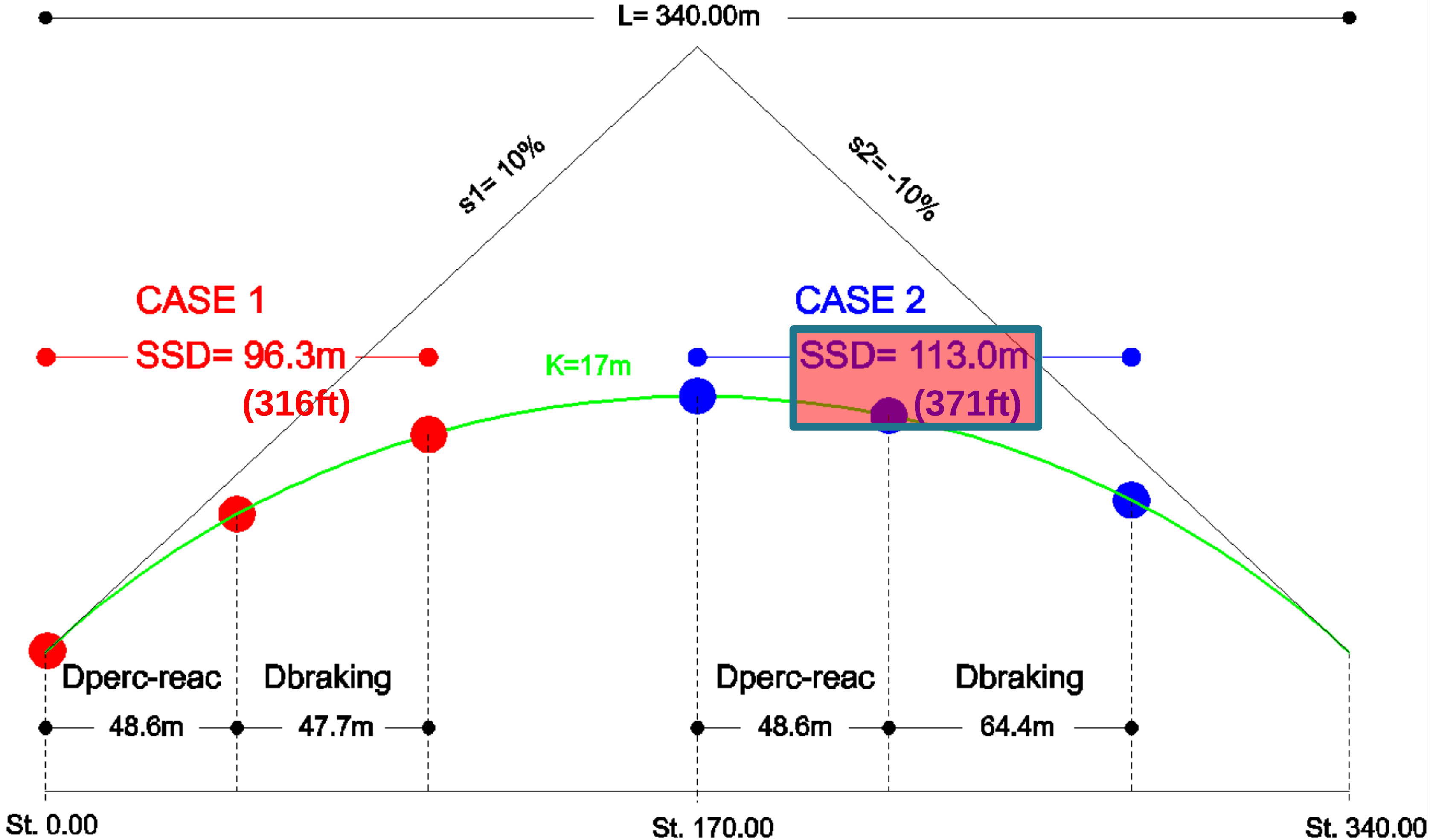
BRAKING CALCULATION ON VARIABLE GRADES (4/5)

- V_{design}=$70_{km/h}$ (45_{mph}), SSD= 105_m (360_{ft}), K=17_m (61_{ft})



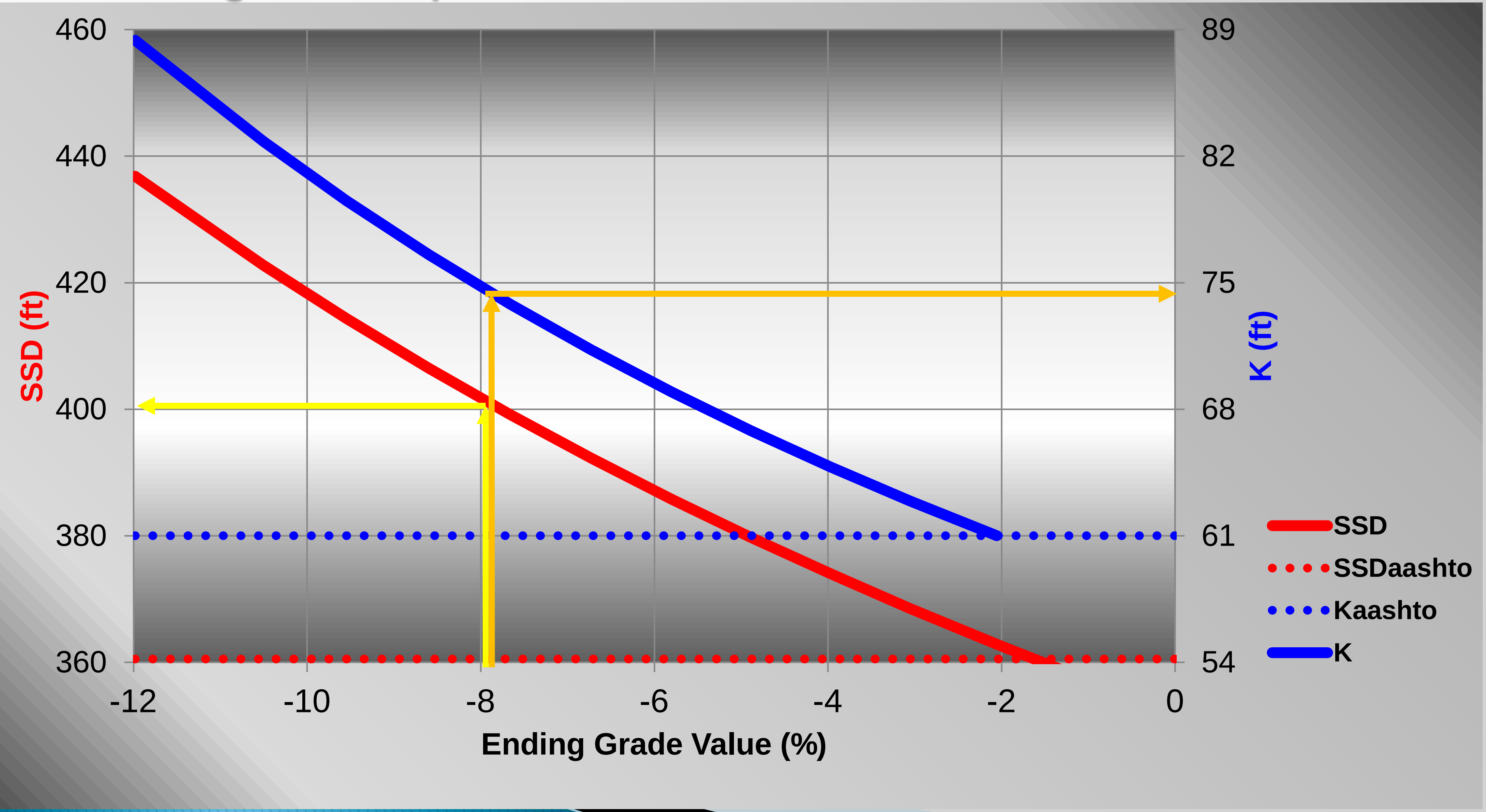
BRAKING CALCULATION ON VARIABLE GRADES (5/5)

- $V_{design}=70_{km/h}$ (45_{mph}), SSD= 105_m (360_{ft}), K=17_m (61_{ft})



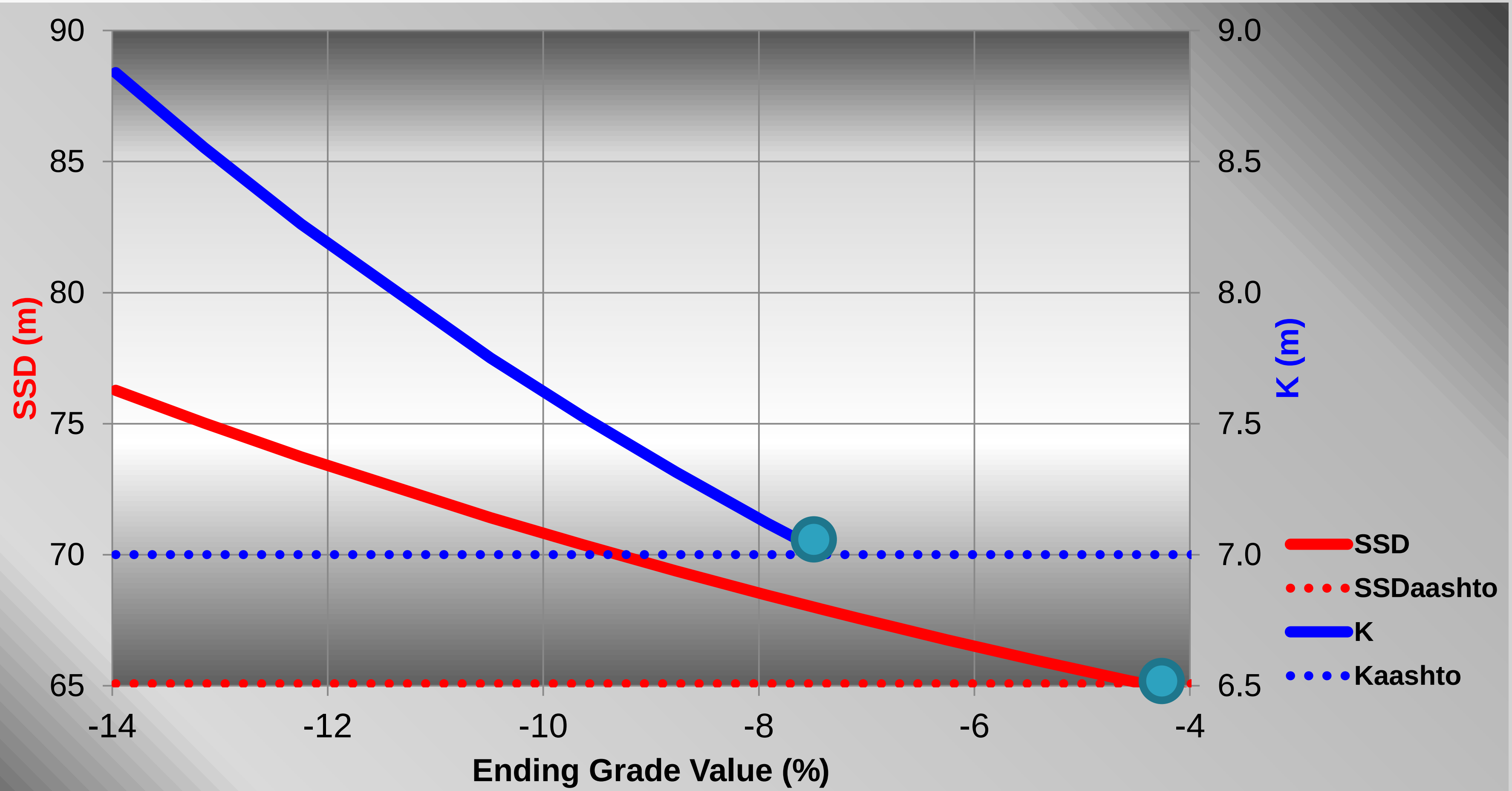
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{design} = 45_{mph}$ $(70_{km/h})$



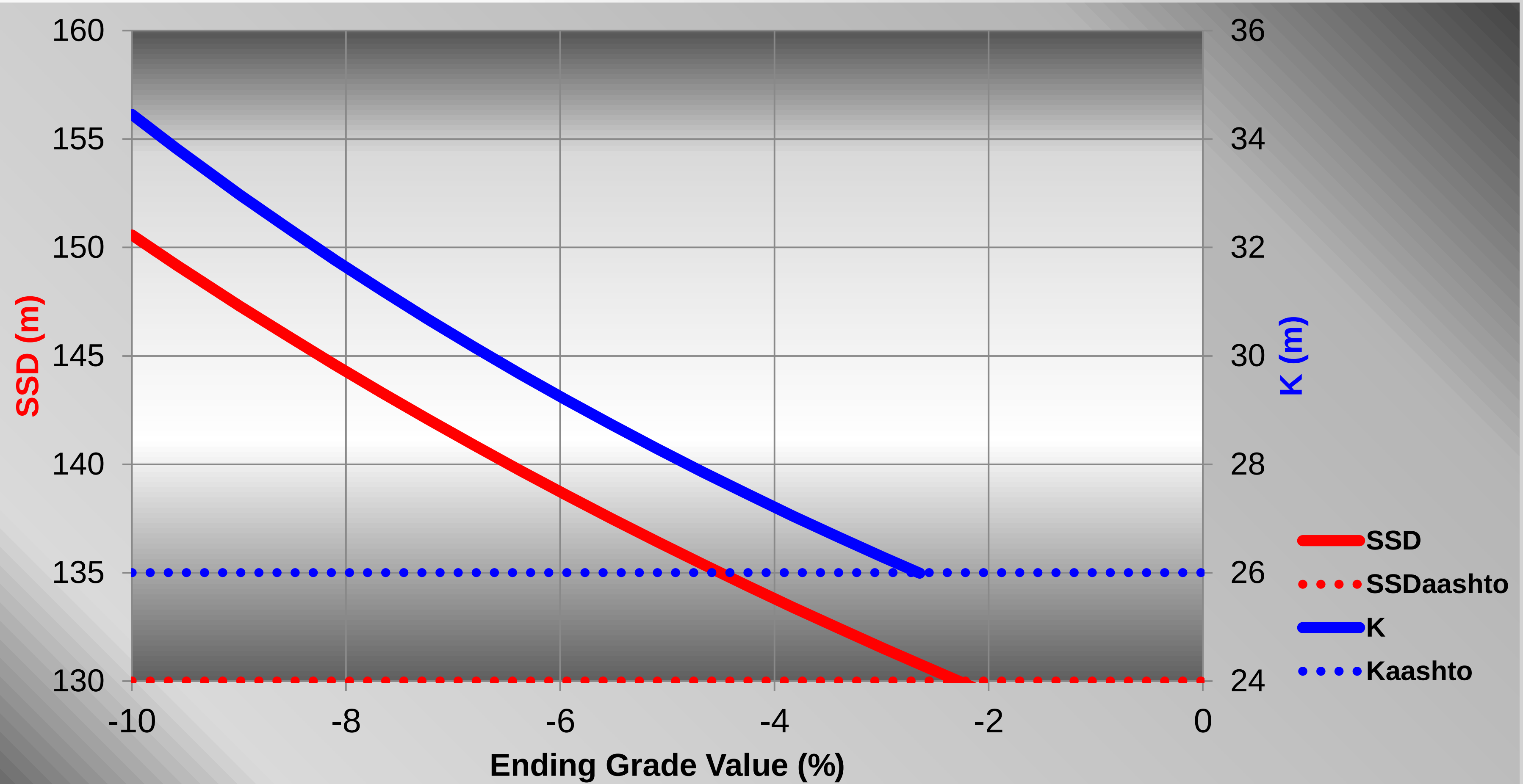
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{design} = 50_{km/h}\ (30_{mph})$



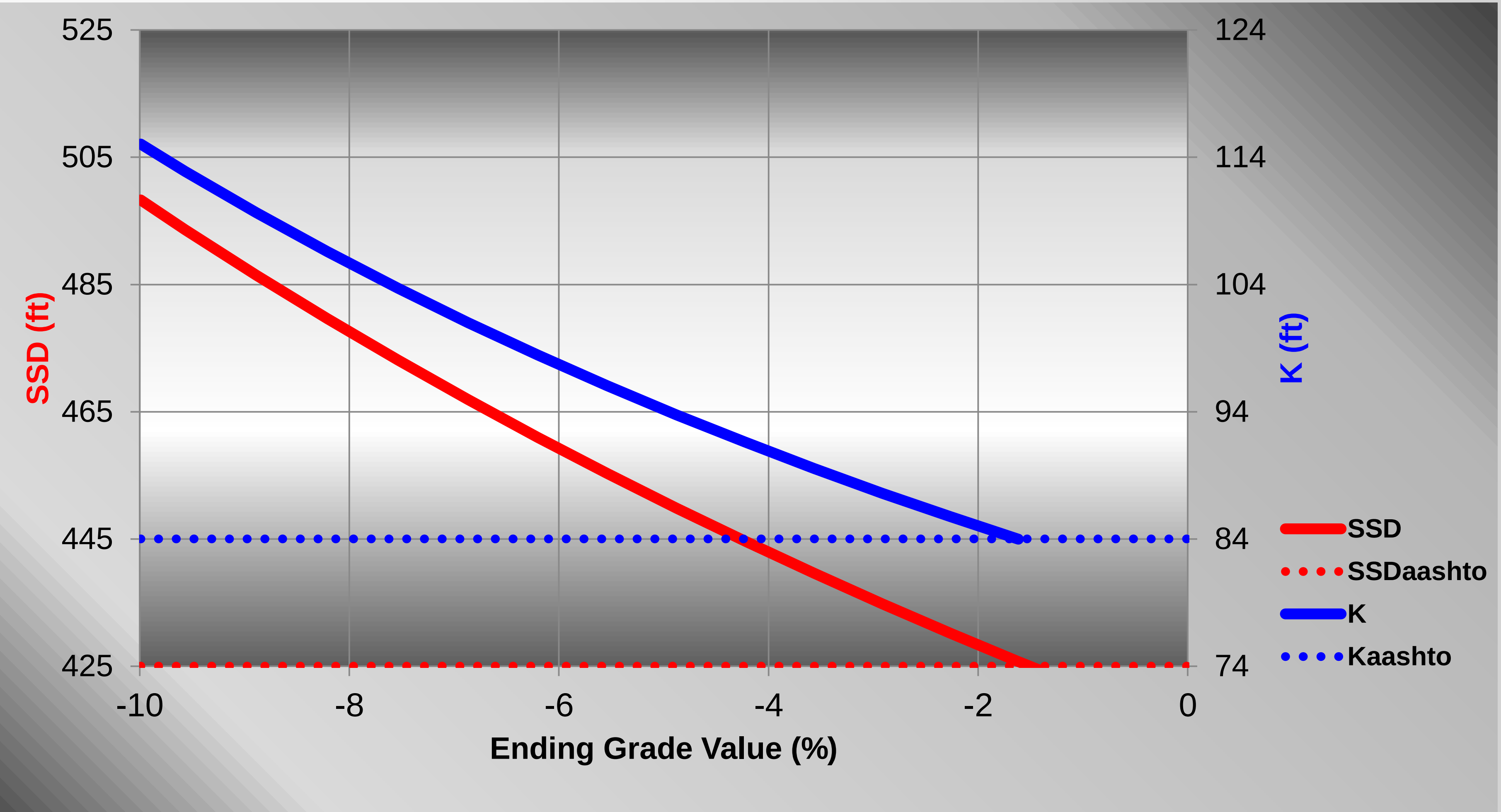
SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{design} = 80_{km/h}\ (50_{mph})$



SUGGESTED CVCR BASED ON SSD ADEQUACY

- $V_{design} = 50_{mph}$ $(80_{km/h})$



SUGGESTED CVCR [V_{design}= 50$_{mph}$ (80$_{km/h}$)]

- Road's Functional Classification
- Exit Grade Value

	Type of Terrain	AASHTO	Exit Grade Value (%) -3	-4	-5	-6	-7	-8	-9	-10
Local Rural	Level	26m 84ft	27m (L>132m) 88ft (L>436ft)	28m (L>134m) 91ft (L>443ft)	29m (L>136m) 95ft (L>451ft)	30m (L>139m) 98ft (L>459ft)	-	-	-	-
	Rolling						31m (L>142m) 102ft (L>468ft)	32m (L>144m) 106ft (L>478ft)		
	Mountainous								33m (L>147m) 111ft (L>488ft)	35m (L>151m) 115ft (L>498ft)
Rural Collectors	Level	26m 84ft	27m (L>132m) 88ft (L>436ft)	28m (L>134m) 91ft (L>443ft)	29m (L>136m) 95ft (L>451ft)	30m (L>139m) 98ft (L>459ft)	-	-	-	-
	Rolling						31m (L>142m) 102ft (L>468ft)			
	Mountainous							32m (L>144m) 106ft (L>478ft)	33m (L>147m) 111ft (L>488ft)	
Rural Arterials	Level	26m 84ft	27m (L>132m) 88ft (L>436ft)	28m (L>134m) 91ft (L>443ft)	-	-	-	-	-	-
	Rolling				29m (L>136m) 95ft (L>451ft)					
	Mountainous					30m (L>139m) 98ft (L>459ft)	31m (L>142m) 102ft (L>468ft)			

metric units (m) US customary units (ft)

SUGGESTED CVCR [V_{design}= 50_{mph} ($80_{km/h}$)]

- Road's Functional Classification
- Exit Grade Value

<table>
<tr><th rowspan="2"></th><th rowspan="2">Type of Terrain</th><th rowspan="2">AASHTO</th><th colspan="8">Exit Grade Value (%)</th></tr>
<tr><th>-3</th><th>-4</th><th>-5</th><th>-6</th><th>-7</th><th>-8</th><th>-9</th><th>-10</th></tr>
<tr><td rowspan="3">Urban Collectors</td><td>Level</td><td rowspan="3">26m
84ft</td><td rowspan="3">27m (L>132m)
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</table>

metric units (m) US customary units (ft)

Conclusions (1/2)

- 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

(2/2)

- 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