STOPPING SIGHT DISTANCE AND HORIZONTAL SIGHTLINE OFFSETS AT HORIZONTAL CURVES

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ABSTRACT

Horizontal curve design criteria implicitly rely on the design speed to produce safe and efficient designs. This is particularly true for horizontal sightline offsets and stopping sight distance criteria. Current design guidance provides a method for calculating minimum horizontal sightline offsets, but is only accurate and valid when both the driver and object are within the limits of the curve. Other methods are available to estimate minimum horizontal sightline offsets when the driver and/or object are not within the curve limits. However, design guidance recommends using the calculated value for offsets as a conservative estimate near the ends of curves.

Speed prediction models and reliability theory were used to estimate the probability that drivers would not have enough sight distance to see, react to, and stop before reaching an object in the roadway if applying horizontal sightline offset criteria when the driver or object are outside the limits of a horizontal curve. Six different scenarios at the approach to a curve and inside the curve were analyzed. Reliability estimates based on minimum horizontal sightline offsets (using current minimum design criteria) and stopping sight distance distributions based on individual driver characteristics show that the probability of drivers not having enough stopping sight distance is much greater at the approach than inside horizontal curves. To improve the consistency of designs, it is suggested that the calculated horizontal sightline offsets be used beyond the limits of the curve (approach and departure tangents) to provide extra sight distance for drivers near the curve.
INTRODUCTION
Stopping sight distance and horizontal sightline offset are considered important design criteria for safe roadway designs and are included in the Federal Highway Administration’s (FHWA) thirteen controlling criteria (1). Horizontal sightline offsets at sharp horizontal curves are often controlled by the minimum stopping sight distance for a given design speed. Current design guidance for minimum stopping sight distance is a function of the design speed, driver perception-reaction times, and driver deceleration rates (2, 3). While the assumed reaction times and deceleration rates are conservative estimates, the design speed is often lower than the actual operating speed of a given road segment (4). For a minimum stopping sight distance, at any point along a curve, there is a minimum horizontal sightline offset. Current design methods for calculating minimum horizontal sightline offsets along horizontal curves are valid only when both the driver and object are within the boundaries of the horizontal curves. Figure 1 illustrates two sight distance situations that indicate how horizontal sightline offsets are impacted by the locations of the driver and object (i.e., the tail lights of a leading vehicle). In the top portion of Figure 1, the driver and object are both within the limits of the curve. The curve labeled “required horizontal sightline offset” is equal to the minimum offset when the driver and object are both within the limits of the curve (i.e., available horizontal sightline offset is equal to the minimum required horizontal sightline offset). The second curve shows what the horizontal sightline offset would be for the same sight distance as on the first curve if the driver was outside the curve and the object was within the curve limits. The offset is less than the value determined for the condition when the driver and object are both within the limits of the curve (the required horizontal sightline offset). This available horizontal sightline offset, which is less than the minimum required horizontal sightline offset, could also occur if: 1) the driver was within the limits of the curve but the object was not, or 2) if the minimum stopping sight distance was greater than the length of the horizontal curve.
Current design methods for estimating minimum horizontal sightline offsets when the driver, the object, or both are outside the limits of the curve include a manually intensive graphical technique (straight-line method) and a computational method that was developed in 1972. Little is known in regards to how the aforementioned computational method from 1972 was developed or how accurate it is (5). The American Association of State Highway and Transportation Officials’ (AASHTO) *A Policy on Geometric Design of Highways and Streets* (herein referred to as the Green Book) recommends using the calculated offsets as conservative.
estimates for locations near the ends of horizontal curves \((3)\). It has been pointed out that using these conservative estimates could lead to higher project costs than necessary due to the need to remove existing buildings, trees and vegetation, or side-slope cut areas \((5)\). The safety impacts of providing less than minimum stopping sight distance has been explored \((2, 6, 7, 8, 9, 10)\); however, all of these studies were limited to the effects of stopping sight distance on vertical curves. The safety impacts of providing the minimum stopping sight distance based on published research are conflicting, indicating that there are no safety impacts associated with providing more sight distance \((2, 6)\), that safety performance worsens as sight distance increases \((7)\), or that safety improves as sight distance increases \((8, 9, 10)\). No studies investigating the safety effects of providing less than the minimum stopping sight distances contained in the Green Book for horizontal curves were found. Also, the safety impacts associated with providing stopping sight distances that exceed the minimum values contained in the Green Book have not been compared to the safety performance of roadways with precisely the minimum stopping sight distance at horizontal curves.

This paper describes and discusses some of the issues relating to how using the conservative estimate for providing the minimum stopping sight distance near the ends of curves impacts horizontal curve design.

**DESIGN METHODS**

**Design Speed and Design Consistency**

Green Book design methods rely on the concept of selecting a design speed, and then using this selected speed to determine minimum or limiting values for various roadway features. Design speeds are supposed to be logical, anticipate the operating speed, and be as high as practical in order to attain safety, mobility, and efficiency within project constraints \((3)\). Selected design speeds should fit the travel desires and behavior of nearly all drivers and should be a high-percentile value in the free-flow speed distribution \((3)\). Design speed is particularly important for the design of horizontal curves as it is used explicitly to determine the minimum radius of curve, superelevation, and minimum stopping sight distance. The Green Book notes that there should not be restrictions placed on sight distances or the use of flatter curves where they can be provided as part of an economical design \((3)\).

Once the design speed for a road is determined, designers are encouraged to use the highest practical values possible for design criteria (e.g. the largest radius for a horizontal curve) on high-speed facilities \((3)\). The Green Book cautions that use of above minimum design criteria on road segments with lower design speeds may encourage drivers to travel at speeds higher than the design speed \((3)\). This is consistent with research findings that observed 85th percentile speeds tend to be higher than the design speed for rural two-lane highways with design speeds that are below 55 mph \((11)\). Design assessment tools have been developed that attempt to reduce the variability in operating speeds that result from the design process. These methods rely on alignment indices, speed distribution parameters (mean operating speed, 85th percentile operating speed, and speed variance), and driver workload estimates \((12, 13, 14)\). These methods predict speeds for successive design features along a given road segment in order to produce road segments with homogenous driver operating speeds and performance.
**Horizontal Sight Offsets and Stopping Sight Distance**

The Green Book provides an objective method to calculate the minimum horizontal sightline offset, as shown in Equation 1 below. The horizontal sightline offset is the distance between the center of the innermost lane on the road and a sight obstruction. This distance must be clear in order to provide a specified stopping sight distance for a given curve radius. Equation 1 was developed based on the geometry of a simple circular curve and, as previously mentioned, is only accurate when both the driver and object on the roadway are within the limits of the curve (i.e., between the point of curvature and point of tangency) as shown in Figure 1.

\[
\text{HSO} = R \left[ 1 - \cos \frac{28.65 \cdot S}{R} \right]
\]

Where

- \( \text{HSO} \) = the minimum horizontal sight offset from the center of the innermost lane in ft;
- \( R \) = the radius of the center of the innermost lane in ft; and
- \( S \) = the minimum stopping sight distance in ft.

The straight-line method suggested in the Green Book can estimate the available sight distance (the distance available that drivers can see an object on the roadway) for situations where either the driver or the object is outside the curve and the other is within the curve, but this method is error prone and tedious. For existing single roadside objects near the ends of curves, this is often the best option if the offset to the object is not as large as the offset calculated using Equation 1.

The computational method suggested by the Green Book can also deal with the same issues as the straight-line method but is not readily available to most designers, was mainly developed for spiral curves, and it is not understood how accurate the method is. This is likely the best method for checking available sight distance, when available to the designer, if the horizontal curve involves a spiral curve and the offset desired is less than the conservative value calculated using Equation 1.

For continuous roadside objects near the ends of curves, a designer must determine whether to provide the minimum stopping sight distance all the way around the curve or whether to provide extra sight distance at the ends of the curve. Extra stopping sight distance can be provided near the ends of curves by using the value calculated from Equation 1. This is particularly true for curves on roads with lower design speeds. Using Equation 1, Figure 2 shows how the minimum horizontal sightline offset varies depending on the radius of curve and design speed. As shown in Figure 2, the minimum offset increases significantly as the radius decreases at lower design speeds; whereas, for higher design speeds, the horizontal sightline offset increases at a much slower rate as the radius decreases. Thus, the potential budget savings (in percent of total project cost) is likely to be highest for projects involving low design speed road segments. The overall cost savings is likely to be highest on projects with high design speeds if the conservative values are not used towards the ends of the curves and other methods are used to reduce the minimum horizontal sightline offsets. However, the difference between the offsets found using Equation 1 and the other two methods are often not significant.
Spiral Roadside Offsets for Stopping Sight Distance

Several papers have been published that developed charts or equations to determine minimum horizontal sightline offsets near the ends of horizontal curves resulting in roadside spiral curves for offsets (5, 15, 16). These equations and charts can be used to determine a profile of minimum horizontal sightline offsets near the ends of curves that allow smaller values than those calculated using Equation 1.

FIGURE 2 Minimum Horizontal Sightline Offsets by Radius of Innermost Lane and Design Speed

The method developed by Mauga (5) used the straight-line method described in the Green Book (conducted numerically to avoid errors), as well as formulas developed in other research (16), to develop roadside spiral curves that begin at a maximum length of the minimum stopping sight distance prior to the PC of the curve (the beginning point starts at the location of the drivers eye, i.e. the center of the innermost lane). The spiral curves then decrease in radius until they reach the minimum radius and maximum horizontal sightline offset at the middle of the curve.

The 1972 method referenced in the Green Book is intended to calculate the horizontal sightline offset for specific locations using a formula along with two figures (15). This method was developed to be used for horizontal curves with and without spiral curve transitions. Use of this method requires the curve radius, sight distance desired, length of the spiral (if any), and the location of interest to be known in order to calculate the offset.
A method to calculate stopping sight distance for any point along an approach tangent, departure tangent, or within a curve given an object with a specific horizontal sight offset at a particular location was developed in 1987 (16). The relationships for this method used the curve radius, horizontal sightline offsets, and lengths related to the driver location, object location, and curve to derive formulas that can be used to calculate the available sight distance for any point of interest near or within a curve.

SPEEDS AT LOCATIONS ALONG HORIZONTAL CURVES

It has been shown that geometric elements affect operating speeds along roadways (17, 18, 19, 20). This is particularly true in regards to sharp horizontal curves. A typical operating speed profile for horizontal curves is shown in Figure 3. As shown, speeds are typically higher on the tangent sections before and after the horizontal curve, lower inside the curve, and involve deceleration and acceleration segments when approaching and departing the curve, respectively.

Many speed prediction models for horizontal curves model the difference in speeds (from approach to midcurve), the acceleration/deceleration, or simply use separate models for approach and midcurve and then take the difference between the two estimates. A summary of some of these models, including what the model predicts (e.g., V85, \(\mu_v\), etc.), the predictors used in the model, and the countries the data came from are shown in Table 1.

![FIGURE 3 Speed Profile for Horizontal Curves](image-url)
### TABLE 1 Speed Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>Year</th>
<th>Country</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{85}$</td>
<td>Radius</td>
<td>1954</td>
<td>USA</td>
<td>(21)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Radius</td>
<td>1986</td>
<td>USA</td>
<td>(22)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Degree of Curvature</td>
<td>1994</td>
<td>USA</td>
<td>(23)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Degree of Curvature</td>
<td>1994</td>
<td>Canada</td>
<td>(24)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Radius</td>
<td>1996</td>
<td>USA</td>
<td>(25)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Radius</td>
<td>1999</td>
<td>USA</td>
<td>(26)</td>
</tr>
<tr>
<td>$V_{85}$</td>
<td>Degree of Curvature, Length of Curve</td>
<td>2000</td>
<td>USA</td>
<td>(27)</td>
</tr>
<tr>
<td>$\mu_{V,Tangent}$, $\sigma_{V,Tangent}$</td>
<td>Percentage Trucks, Posted Speed, Grade, Residential Land Use, Sight Distance, Intersections, Paved Width, Gravel Shoulder Width, Untreated Shoulder Width, Clear Zone, Flat Curve (radius &gt; 1,700 ft)</td>
<td>2005</td>
<td>USA</td>
<td>(18)</td>
</tr>
<tr>
<td>$\mu_{V,Curve}$, $\sigma_{V,Curve}$</td>
<td>Sight Distance, Residential Land Use, Superelevation</td>
<td>2005</td>
<td>USA</td>
<td>(18)</td>
</tr>
<tr>
<td>Deceleration Rate</td>
<td>Left-Hand Curve, Radius, Approach Tangent Length, Curve Length, Roadside Hazard Rating</td>
<td>2010</td>
<td>USA</td>
<td>(29)</td>
</tr>
<tr>
<td>Acceleration Rate</td>
<td>Left-Hand Curve, Radius, Approach Tangent Length, Curve Length, Roadside Hazard Rating, Departure Tangent Length</td>
<td>2010</td>
<td>USA</td>
<td>(29)</td>
</tr>
<tr>
<td>$V_{Posted}$, $\mu_{V}$, $\sigma_{V}$</td>
<td>Access Points, Traffic Volume, Residential Land Use, Industrial Land Use, Curb and Gutter, Grade, On-Street Parking, Median or Turning Lane, Shoulder Width, At-Grade Rail Crossing, Left-Hand Curve, Crest Curve, Wooded Adjacent Land, Percentage Trucks</td>
<td>2011</td>
<td>USA</td>
<td>(11)</td>
</tr>
<tr>
<td>$V_{85,Tangent}$, $V_{85,Curve}$</td>
<td>Radius, Length of Curve, Preceding Tangent Length</td>
<td>2013</td>
<td>India</td>
<td>(30)</td>
</tr>
<tr>
<td>$\mu_{V}$, $\sigma_{V}$</td>
<td>Radius, Length of Curve</td>
<td>2013</td>
<td>India</td>
<td>(30)</td>
</tr>
<tr>
<td>$\Delta V_{85}$</td>
<td>Radius, Length of Curve, Tangent Velocity</td>
<td>2013</td>
<td>India</td>
<td>(30)</td>
</tr>
</tbody>
</table>

$V_{85} = 85^{th}$ percentile operating speed, $\mu_{V} = $ mean operating speed, $\sigma_{V} = $ speed variance, $V_{Posted} = $ posted speed limit, $\Delta V_{85} = $ the change in $85^{th}$ percentile operating speed

Radius or degree of curvature (a function of radius) is included in the majority of the models shown in Table 1. From these models, it has been shown that smaller curve radii are associated with larger speed differences between the approach tangent and the mid-point of the curve. Similarly, smaller curve radii are associated with larger deceleration rates approaching and entering horizontal curves.
Stopping sight distance has been shown to have a statistically significant association with vehicle speeds (18). The findings indicate that as available sight distance increases, the average speeds within a curve increase. The findings also indicate that speeds along tangent sections preceding curves had a quadratic relationship with speed, including an overall increase in average speeds as available sight distance increased. No statistically significant relationship between available sight distance and speed variance was found for either location. It was found that locations with a wider roadside clear zone had lower speed variance along the approach tangent.

PROBABILITY OF NON-COMPLIANCE

Methods

Reliability theory has been used extensively in civil engineering applications to analyze and create load and resistance factor design criteria (31), analyze and make reliability based decisions on aging bridges (32), assess and estimate safety factors for existing structures (33, 34), analyze water distribution networks (35, 36), and to analyze water resource allocation problems (37). It has been used on a smaller scale in transportation engineering applications, but has been suggested for use in transportation safety applications when crash modification factors are not available for a design element or treatment (38). For this paper, reliability theory was used to calculate the probability that a driver would not have enough sight distance to react and stop given an object on the road for the two situations shown in Figure 1. These situations include, for each case, when 1) the driver is approaching a curve and the object is within the limits of a curve and, 2) the driver and object are both within the limits of the curve. The driver and object are both in the innermost lane for all cases analyzed. The reliability was computed using the equation for stopping sight distance and the distribution parameters (mean and standard deviation, where applicable) for the variables in the equation. The equation for stopping sight distance is given by the Green Book as shown in Equation 2 (3).

\[
SSD = \frac{V^2}{2g\left(\frac{a}{g} + G\right)} + V \cdot t_r
\]  

(2)

Where

- SSD = stopping sight distance in ft;
- V = the velocity of a vehicle in ft/s;
- a = deceleration rate in ft/s²;
- g = 32.2 ft/s²;
- G = the average grade (decimal); and
- t_r = reaction time in seconds.

Minimum stopping sight distance is the distance required for a driver to perceive and react to an object, and then stop. This distance varies from driver to driver depending on the operating speed, perception-reaction time, deceleration rate, and the average grade. Reliability theory specifies that the performance function (in this case, Equation 2 for stopping sight distance) be used and that the mean value and standard deviation for the performance function be calculated. The mean value for the performance function was calculated by using the mean values for V, a, and t_r along with the values for G (a constant that was specific to the case being analyzed) and g.
The standard deviation was calculated using the formula shown in Equation 3:

\[
\sigma_{SSD} = \sqrt{\sum_i \left( \frac{dSSD}{dx_i} \right)^2 \sigma_{x_i}^2}
\]  

(3)

Where

- \( \sigma_{SSD} \) = the standard deviation of the performance function;
- \( \frac{dSSD}{dx_i} \) = the derivative of the performance function with respect to variable \( x_i \); and
- \( \sigma_{x_i} \) = the standard deviation of variable \( x_i \).

The derivatives of the variables for minimum stopping sight distance are shown in Equations 4 through 7.

\[
\frac{dSSD}{dV} = \frac{at + gGt + V}{a + gG}
\]  

(4)

\[
\frac{dSSD}{da} = -\frac{V^2}{2(gG + a)^2}
\]  

(5)

\[
\frac{dSSD}{dG} = 0
\]  

(6)

\[
\frac{dSSD}{dt} = V
\]  

(7)

As shown in Equations 2, 4, 5, and 7, car velocity (speed) is an important component of stopping sight distance and the distribution parameters for velocity were used in the reliability analysis. To estimate these parameters, Equations 8 through 11 were used:

\[
V_{\text{curve}} = 46.664 + 3.44x10^{-3} \cdot SD - 2.639 \cdot RES - 2.541 \cdot DC + 7.954 \cdot SE - 0.624 \cdot SE^2
\]  

(8)

\[
\sigma_{v_{\text{curve}}} = 4.158 + 0.236 \cdot DC - 0.199 \cdot SE
\]  

(9)

\[
V_{\text{tangent}} = 57.137 - 0.071 \cdot TR - 3.082 \cdot PSL_{50} - 0.131GR - 1.034 \cdot RES + 2.38x10^{-3} \cdot SD - 1.67x10^{-3} \cdot SD^2 - 0.422 \cdot INT
+ 0.040PAV + 0.394GSW + 0.054USW - 2.233FC
\]  

(10)

\[
\sigma_{v_{\text{tangent}}} = 5.9816 + 1.4280 \cdot PSL_{50} + 0.061 \cdot GR + 0.292 \cdot INT
- 0.038 \cdot PAV - 0.012 \cdot CLR
\]  

(11)
Where

\[ V_{\text{curve}} = \text{the mean speed on the curve in mph}; \]
\[ \sigma_{\text{curve}} = \text{the standard deviation of speed on the curve in mph}; \]
\[ V_{\text{tangent}} = \text{the mean speed on the approach tangent in mph}; \]
\[ \sigma_{\text{tangent}} = \text{the standard deviation of speed on the approach tangent in mph}; \]
\[ \text{SSD} = \text{stopping sight distance in ft}; \]
\[ a = \text{deceleration rate in ft/s}^2; \]
\[ g = 32.2 \text{ ft/s}^2; \]
\[ G = \text{the average grade in \%}; \]
\[ t_r = \text{reaction time in seconds}; \]
\[ \text{TR} = \text{percentage of trucks}; \]
\[ PSL_{50} = \text{equal to 1 if the posted speed limit is 50 mph, and equal to 0 otherwise}; \]
\[ \text{GR} = \text{highway grade (%)}; \]
\[ \text{RES} = \text{equal to 1 if the segment has 10 or more residential driveways per mile, 0 otherwise}; \]
\[ \text{SD} = \text{sight distance (ft)}; \]
\[ \text{INT} = \text{equal to 1 if an intersection is located within 350 ft before or after the location where the speed was collected, 0 otherwise}; \]
\[ \text{PAV} = \text{pavement width, includes the traveled way and both paved shoulders (ft)}; \]
\[ \text{GSW} = \text{total gravel shoulder width (ft)}; \]
\[ \text{USW} = \text{total untreated shoulder width (ft)}; \]
\[ \text{CLR} = \text{roadside clear zone, includes the total gravel and total untreated shoulders (ft)}; \]
\[ \text{FC} = \text{equal to 1 if the spot is located on a flat curve (radius larger than 1,700 ft), 0 otherwise}. \]

These models were selected for the analysis due to inclusion of curve and sight distance variables in the model specification. Additionally, the same dataset was used to model the parameters for speed at both the tangent preceding the curve and for the curve. The value used for TR in all cases was 0% to limit the results of the analysis to the effects on passenger cars. CLR was based on the required clear zone to create the minimum sight distance per the Green Book for each case.

Distribution parameters for deceleration rate and perception-reaction time were taken from the 1997 NCHRP report on stopping sight distance (2). These values, as well as the value for g, are shown in Table 2.

**TABLE 2  Variable Distribution Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( a ) (ft/s(^2))</th>
<th>( t_r ) (s)</th>
<th>( g ) (ft/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>16.42</td>
<td>1.5</td>
<td>32.2</td>
</tr>
<tr>
<td>STDEV</td>
<td>2.898</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>
Reliability indices were used to calculate the probability of non-compliance. For this study, the probability of non-compliance was defined as the probability that a driver would not have enough stopping sight distance available to see an object on the road, react, and stop before reaching it (i.e. the required stopping sight distance for the driver is greater than the available sight distance). Figure 4 illustrates this concept. The dashed line represents the available sight distance for a location; the solid black line is the distribution of stopping sight distances required by drivers caused by varying reaction times, deceleration rates, and vehicle operating speeds; and the probability of non-compliance is the area under the probability density function to the right of the available sight distance line.

Once the mean and standard deviation of the performance function were calculated, the reliability index was calculated using Equation 12 \((39)\). The reliability index was then used to estimate the probability of non-compliance.

\[
\text{RI} = \frac{\mu_{\text{SSD}} - \text{ASD}}{\sigma_{\text{SSD}}}
\]

Where
- \(\text{RI} = \) the reliability index;
- \(\mu_{\text{SSD}} = \) the mean stopping sight distance;
- \(\text{ASD} = \) the available sight distance; and
- \(\sigma_{\text{SSD}} = \) is as previously defined in Equation 3.
**Results**

The equations and variables defined previously were used to calculate the probability of non-compliance for tangents and curves for six different cases. For each case, the following two scenarios were analyzed: 1) the driver is on the tangent approaching the curve and the object is within the limits of the curve, and 2) both the driver and the object are within the limits of the curve. For each case in this analysis, the available sight distance was equal to the minimum stopping sight distance found in the Green Book for the given design speeds. Similarly, the design speed was assumed equal to the posted speed limit. The six cases included three curves with 50 mph speed limits and three curves with 55 mph speed limits (8%, 4%, and 2% superelevations for each speed limit). All six cases were for two-lane rural highways that were not near intersections, had a paved width of 24 ft, a gravel shoulder width of 2 ft, and a grade of -4%. The values used for superelevation in the six cases were selected to be within the limits of the values observed in the data that were used in estimating the speed models. Available sight distance typically varies slightly depending on the driver’s eye height, driver’s lane position, object height, and object lane position. The results of the analysis are shown in Table 3.

**TABLE 3 Reliability Analysis Results**

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Posted (Design) Speed (mph)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td><strong>Superelevation (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Available (Required) Sight Distance (ft)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>425</td>
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<td>425</td>
<td>495</td>
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</tr>
<tr>
<td><strong>Radius (ft)</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>760</td>
<td>928.3</td>
<td>1044.3</td>
<td>962.7</td>
<td>1189.3</td>
<td>1347.8</td>
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<tr>
<td><strong>Tangent Speed (mph)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Mean</td>
<td>57.0</td>
<td>57.0</td>
<td>57.0</td>
<td>60.2</td>
<td>60.2</td>
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<tr>
<td>STDEV</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>4.5</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td><strong>Curve Speed (mph)</strong></td>
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<td></td>
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<tr>
<td>Mean</td>
<td>53.7</td>
<td>55.3</td>
<td>48.6</td>
<td>57.9</td>
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<td>STDEV</td>
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<td>5.1</td>
<td>4.0</td>
<td>4.5</td>
<td>4.8</td>
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<tr>
<td><strong>Tangent Stopping Sight Distance (ft)</strong></td>
<td></td>
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<tr>
<td>Mean</td>
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<td>356.7</td>
<td>389.8</td>
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<td>STDEV</td>
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<td>23.6</td>
<td>24.5</td>
<td>24.5</td>
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<tr>
<td><strong>Curve Stopping Sight Distance (ft)</strong></td>
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<tr>
<td>Mean</td>
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<td>338.8</td>
<td>274.8</td>
<td>366.1</td>
<td>376.8</td>
<td>306.4</td>
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<td>STDEV</td>
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<td>22.6</td>
<td>20.2</td>
<td>23.5</td>
<td>24.0</td>
<td>21.4</td>
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<tr>
<td><strong>Reliability Index</strong></td>
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<td></td>
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<tr>
<td>Tangent</td>
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<td>2.89</td>
<td>2.89</td>
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<tr>
<td>Curve</td>
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<td>3.81</td>
<td>7.45</td>
<td>5.48</td>
<td>4.93</td>
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<td><strong>Probability of Non-Compliance</strong></td>
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<tr>
<td>Tangent</td>
<td>0.1930%</td>
<td>0.1930%</td>
<td>0.1930%</td>
<td>0.0009%</td>
<td>0.0009%</td>
<td>0.0009%</td>
</tr>
<tr>
<td>Curve</td>
<td>0.0001%</td>
<td>0.0070%</td>
<td>0.0000%</td>
<td>0.0000%</td>
<td>0.0000%</td>
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<tr>
<td><strong>Available Sight Distance Required on Tangent to obtain same Reliability Index as Curve (ft)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>467.2</td>
<td>446.8</td>
<td>533.4</td>
<td>524.1</td>
<td>510.8</td>
<td>607.1</td>
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</table>
The tangent speed and curve speed parameters shown in Table 3 are the estimated values that were used to calculate the stopping sight distance mean and standard deviation at both the tangent and curve. These values, along with the available sight distance, were then used to calculate the reliability indices. The reliability indices were then converted into the probability of non-compliance. Finally, the amount of sight distance required along the tangent nearing the curve that was needed to produce a reliability index that was the same as that computed for vehicles and objects within the limits of the curve was calculated for each case.

As shown in the results, the probability of non-compliance is much greater for the tangents than the curves when the minimum stopping sight distance is provided on the tangent approaching the horizontal curve (e.g. 0.1930 percent vs. 0.0001 percent). The last row in Table 3 shows the amount of stopping sight distance that would be required at the approach of the curve in order to have the same low probability of non-compliance as inside the curve. This additional sight distance could be attained by using the offset estimate found using Equation 1 near the ends of the curve rather than using roadside spiral offsets.

The probability of non-compliance for all cases presented in this section is low (less than 0.2% for the tangents and less than or equal to 0.007% for the curves). In practical terms this means that, given that there is an object on the roadway, 1 in 518 drivers on the approach tangent for the first three cases would not have enough sight distance available to see the object, react to it, and come to a stop before reaching it. For drivers on the approach tangent in the last three cases, 1 in 111,000 drivers would not have enough sight distance. For drivers in the curves, 1 in 1,000,000 drivers for the first case, 1 in 14,285 drivers in the second case, and essentially 0 drivers in cases 3 through 6, would not have enough stopping sight distance available.

CONCLUSIONS

The operating speed profile is an important concept in geometric design. Current design policy does not explicitly consider this concept and relies on the assumption that establishing a design speed will accommodate operating speed variability. The concept of design consistency has been proposed and provides designers with a tool that incorporates a speed profile into the analysis, but this tool is not required for design and is not used extensively.

Horizontal curve design criteria rely on the design speed to result in safe and efficient designs, as currently established. Speed prediction models and reliability theory were used to estimate the probability that drivers would not have enough sight distance to see, react to, and stop before reaching an object in the roadway for six different scenarios at both the approach to a curve and inside the curve if only the minimum stopping sight distance was provided at each location (i.e. if spiral curve offsets were used to make the available sight distance equal to the minimum stopping sight distance). The available sight distance near and along horizontal curves is the distance that is available to drivers with specific eye heights and object heights, and with specific driver and object locations within the lane. For the analysis in this paper, the effects of the variations in these parameters were assumed to be negligible.

Results from the reliability analysis indicate that the probability of non-compliance is much greater at the approach to curves than inside horizontal curves. In order to improve the consistency of reliability, it is suggested that the offsets used inside the curve for meeting stopping sight distance requirements be used near the ends of the curve to provide extra sight distance for drivers approaching or departing the curve.

One of the potential benefits to estimating the reliability index for stopping sight distance is that it could potentially be used as a design consistency measure. This would require that speed models be used along with geometric data to calculate the reliability indices for the
approaches and inside the curves for consecutive curves along a roadway segment. Such models could be included in design consistency software such as the Interactive Highway Safety Design Model (IHSDM). However, before this is done, research establishing whether there is a link between stopping sight distance reliability and safety performance should be conducted.

REFERENCES


