# AN OPERATIONAL AND SAFETY EVALUATION OF ALTERNATIVE HORIZONTAL CURVE DESIGN APPROACHES ON RURAL TWO-LANE HIGHWAYS

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## ABSTRACT

This paper evaluates the effects of superelevation on 85th percentile speeds and accident experience as well as the effects of side friction demand on accident experience at horizontal curves on rural two-lane highways. These evaluations were conducted as part of research toward development of a design consistency evaluation model for the United States.

The operating speed analysis verified previous models that used degree of curvature, length of curve, and deflection angle as independent variables for estimating 85th percentile speed on curves. The analysis also found superelevation to be a statistically significant independent variable.

Independent variables in the accident analysis included degree of curvature, operating speed reduction, superelevation deficiency, and implied side friction demand. Operating speed reduction and superelevation deficiency were found to be significant accident predictors; however, implied side friction demand was the strongest accident surrogate.

Comparisons of alternative horizontal curve design methods, with respect to which speed should be used for the design of curves, were made. The 85th percentile speed on a curve was the strongest performer of four curve design ideologies and is recommended for use in horizontal curve design.

Superelevation has significant effects on 85th percentile speed on rural two-lane horizontal curves. Operating speed reduction, superelevation deficiency and side friction demand based on 85th percentile operating speeds have significant effects on the safety of horizontal curves. These findings provide further support of the adoption of an operating-speed based design procedure for two-lane rural highways in the U.S.

## INTRODUCTION

Average accident rates are higher on horizontal curves than on tangent sections of rural two-lane highways. Consequently, considerable research has focused on the operational and safety aspects of horizontal curves. Radius or degree of curvature consistently tops the list of geometry variables that most significantly affect operating speeds and accident experience on horizontal curves. Less consistent results regarding other geometry variables—including length of curve, deflection angle, superelevation rate, presence of transition curves, lane width, shoulder width, and the location of a curve relative to other horizontal and vertical alignment features—suggest that their effects may be statistically significant but lesser in magnitude.

In refining operating-speed-based horizontal alignment consistency evaluation models for U.S. use, the Texas Transportation Institute examined all of the above-listed geometry variables, except superelevation rate (*1*). Several factors motivated the follow-up research described herein to evaluate alternative speed assumptions for superelevation design and the corresponding role of superelevation in consistency evaluation. First, although the basic laws of physics link speed, radius of curvature, side friction, and superelevation rates, previous empirical studies have not found a significant relationship between superelevation rate and operating speeds on curves. Second, previous accident studies have found significant relationships between superelevation deficiency and accident experience, and between side friction and accident rates (*2-4*). Third, U.S. policy on the application of superelevation may contribute to observed disparities between design and operating speeds on horizontal curves in the United States; similar disparities observed in other countries led to revisions in the speeds upon which superelevation design was based.

The research described herein sought to better understand the interrelationship between superelevation and operating speeds as a basis for determining the appropriate relationship between superelevation design and consistency evaluation in horizontal alignment design policy. Analyses were performed to determine the statistical significance of relationships between: (1) 85th percentile speed on horizontal curves and superelevation, (2) accident experience on horizontal curves and superelevation deficiency (based upon estimated operating speeds), and (3) accident experience on horizontal curves and implied side friction (based upon estimated operating speeds). The scope was limited to rural, two-lane highways in level or rolling terrain.

The remainder of the paper is divided into five sections. First, a literature review summarizes previous research that motivated this study. The second and third sections discuss the analysis methodology and results. The final sections present conclusions and recommendations.

## LITERATURE REVIEW

U.S. horizontal alignment design policy is presented in *A Policy on Geometric Design of Highways and Streets* by the American Association of State Highway and Transportation Officials (AASHTO) (*5*). The policy uses the design-speed concept to provide alignment consistency with respect to operating speeds. The design-speed concept works well when the design speed adequately represents the desired speeds of drivers on a roadway. If the design speed is lower than drivers' desired speeds, however, disparities between operating speed and design speed generally result.

Recent studies have observed disparities between design and operating speeds on rural two-lane highways. Researchers in both the United States and Australia have found that 85th percentile speeds exceeded design speeds on curves with design speeds less than 90-100 km/h and were lower than design speeds on curves with design speeds greater than about 100 km/h (*1, 6-8*).

The disparity between operating and design speed reveals several flaws in current U.S. design policy. First, design speed has meaning only on curves, not on tangents. AASHTO provides no quantitative guidance to establish maximum tangent lengths to control operating speeds. Secondly, AASHTO encourages the use of above-minimum design values on horizontal curves, which may encourage operating speeds greater than the design speed of the controlling geometric element (*9*). Current AASHTO policy provides no methods for detecting and resolving operating speed inconsistencies because it assumes they cannot occur.

AASHTO uses the application of superelevation as the primary mechanism for ensuring operating speed consistency. However, the procedure for distributing superelevation on curves less sharp than the maximum degree of curvature employs the flawed assumption that drivers will operate no faster than the design speed even on curves where they feel comfortable operating at higher speeds.

Weaknesses in the design-speed concept have spurred alternative approaches to horizontal curve design. Several countries have addressed the disparity between design speed and operating speed by updating their design procedures to include checks of actual driver speed behavior.

For example, German design guidelines require that design speed and operating speed be tuned within certain tolerances, and operating-speed consistency is checked using acceptable ranges for successive curve radii (*10*); if checks reveal a consistency problem, then transition sections are considered or the design speed is increased. Australian guidelines also provide an iterative method for the design of low-speed alignments. McLean (*11*) observed that 85th percentile speeds on alignments designed for speeds of 100 km/h or more were generally lower than the design speed, in which case no iteration is necessary and all elements are designed for the design speed. For low-speed alignments, however, estimated 85th percentile speeds are used as the design condition (*12*).

## ANALYSIS METHODOLOGY

This research evaluated whether operations and accident experience in the United States supported refinements in the design-speed concept, similar to those adopted in Germany and Australia, to more accurately reflect current driver speed behavior. The operations analysis examined the effect of superelevation rate on 85th percentile operating speeds on curves. The accident analysis examined four variables—radius or degree of curvature, operating speed reduction, superelevation deficiency, and implied side friction demand—as indicators of accident experience on horizontal curves.

Two data bases were used: a speed-geometry data base, and an accident-geometry data base. The speed-geometry data base includes 85th percentile speeds and geometry characteristics for 138 simple circular curves and 78 approach tangents on rural two-lane highways in five states: New York, Pennsylvania, Oregon, Washington, and Texas (*1*). For each site, the 85th percentile speed was estimated based upon a minimum of 100 free-flow, passenger vehicle speeds.

The accident-geometry data base includes detailed accident and geometry data for 247 curves on 13 Texas roadways. The roadway segments in the accident study were rural two-lane highways at least 4.0 km in length and at least 0.8 km from the end of the roadway and from city limits, eliminating the effects of controlled speed environments. Curves with intersections on or within 150 meters of the curve were excluded to avoid intersection-related accidents. Since each direction of each curve has different approach characteristics, each direction was considered a separate site, resulting in a total of 494 curve sites. Curve geometry data included degree of curvature, length of curve, deflection angle, superelevation rate (measured in the field), and preceding curve features.

Seven years of accident data were obtained for the curve sites. Individual police accident reports were reviewed to define the location and cause of each accident. Accidents were excluded from the data base if caused by any of the following: (1) driver asleep, (2) animal on the roadway, (3) passing, parked, or turning vehicle, (4) bicyclist or pedestrian related, or (5) mechanical defect in the vehicle. In total, the data base contained 226 passenger vehicle accidents.

## ANALYSIS RESULTS

### Operating Speed Analysis

In previous research throughout the world, 85th percentile speeds on curves were typically modeled as a function of only radius or degree of curvature (*13-20*). Several different model forms—including linear, inverse, and exponential—have been used with similar goodness of fit. For this data base, a simple linear regression equation fit the data well and was preferred due to its simplicity (*1*):

$$V_{85} = 103.6 - 1.95\,D = 103.6 - \frac{3405}{R} \qquad (eq.1)$$

where $V_{85}$ = 85th percentile speed at the midpoint of the curve (km/h), D = degree of curvature (°), and R= radius (m). This equation had an $R^2$ value of 0.80 and a root mean square error (MSE) value of 5.2 km/h.

In addition to radius or degree of curvature, length of curve and the interaction between degree of curvature and length of curve (deflection angle) were also statistically significant and offered useful insights into driver speed behavior on curves. The resulting multiple linear regression equation is:

$$V_{85} = 102.4 - 1.57D + 0.012L - 0.10\Delta =$$

$$102.44 - \frac{2742}{R} + 0.012L - 0.10\Delta \qquad (eq.2)$$

where: $V_{85}$, D, and R are as previously defined, L = length of curve (m), and $\Delta$ = deflection angle (°). This equation has an $R^2$ of 0.82 and a root MSE of 5.0 km/h. This equation indicates that on curves with radii greater than about 400 m speeds at the midpoint increase as the length of curve increases. For curves with radii less than 400 m, however, 85th percentile speeds decrease as the length of curve increases. This result is intuitive. On short, sharp curves drivers tend to flatten the curve and decelerate less. Whereas on longer, sharp curves, drivers are less likely to flatten the curve, having greater length to decelerate to the curve midpoint.

To text the effect of superelevation rate, it was added as an independent variable in each of these equations. It was hypothesized that if all other curve geometry parameters were held constant, the 85th percentile operating speed would increase as the superelevation rate increased. Statistical analysis indicated that, when added to the simple linear regression equation (*eq. 1*), superelevation was statistically significant. The resulting equation was:

$$V_{85} = 102.0 - 2.08D + 40.33e = 102.0 - \frac{3632}{R} + 40.33e \qquad (eq.3)$$

where: $V_{85}$ , D, and R are as previously defined and e = superelevation rate (m/m). The $R^2$ for this model was 0.81 with a root MSE = 5.15 km/h.

Superelevation was also statistically significant when added to the multiple-linear regression equation (*eq. 2*). The resulting equation was:

$$V_{85} = 99.6 - 1.69D + 0.014 - 0.13\Delta + 71.82e =$$

$$99.6 - \frac{2951}{R} - 0.014L - 0.13\Delta + 71.82e \qquad (eq.4)$$

where: $V_{85}$, D, R, L, $\Delta$, and e are as previously defined. This model has an $R^2$ value of 0.84 and a root MSE of 4.80

The results confirm that superelevation rate is statistically significant and that speeds at the curve midpoint increase with increasing superelevation rate. Including the superelevation rate in speed estimation equations improves the $R^2$ of the regression equation by only 1-2 percentage points. Over the range of practical values (0.02 to 0.08), superelevation makes a difference of 4.3 km/h on the overall estimated speed (*eq. 4*). When compared to the root MSE (4.80 km/h), it appears that while statistically significant and academically interesting, the practical effect of superelevation is small. However, to assess whether the marginal improvement in explanatory power justified the cost of including additional independent variables, all four equations were used to estimate operating speed reductions, superelevation deficiencies, and implied side friction demand in the accident analysis.

### Accident Analysis

Four independent variables were analyzed as accident surrogate measures: radius (or degree) of curvature, operating speed reduction (from the approach tangent to the curve midpoint), superelevation deficiency at the assumed speed on the curve, and implied side friction demand at the assumed speed on the curve.

The basic model form throughout the analysis is:

$$\ln(\,accident\ rate + 0.1\,) = f(\,surrogate\ measure\,) \qquad (eq.\ 5)$$

The natural logarithm of the accident rate was used because the frequency of accidents is assumed to be Poisson. The ln (*accident rate*) is assumed to be normally distributed, as required by standard regression techniques. Since more than 50 percent of the curves experienced no accidents during the study period, a constant 0.1 was added to each accident rate *before* the logarithmic transformation.

Average annual daily traffic (AADT) and length of curve have significant effects on accident rates (*3*). Using AADT and length of curve in the accident rate simplifies the modeling process, but requires two assumptions: (1) that their relationship to accident frequency (accidents/year per site) is linear, and (2) the relationships have slopes of 1.0. These assumptions were tested and verified, and AADT and length of curve were included in the denominator of the accident rate. The accident rate used was accidents per million vehicle kilometers.

Due to the limited number of curve sites and the large number of sites with no accidents during the seven-year study period, curve sites with similar levels of the independent variable were grouped. Each group contained at least 30 sites. Within each group, mean accident rate and mean value of the independent variable were computed. The group means were regressed using the model form in equation 5.

*Radius or Degree of Curvature*

Many research efforts have identified radius or degree of curvature as a strong indicator of accident experience (*1-4,13*, *21*). The mean radius and degree of curvature for each category were computed and regressed against the natural logarithm of the mean accident rate within each category. The resulting regression equation was:

ln ( *Mean Accident Rate + 0.1* )
= -2.2 + 0.064 (*Mean Degree of Curvature* )
= -2.2 + 111.8 / (*Mean Radius of Curvature*) (*eq. 6*)

This relationship had an $R^2 = 0.79$, MSE = 0.03, and p-value = 0.0034. The results support previous results that the sharpness of curve is significant. The high $R^2$ results from the grouping of sites and, therefore, does not reflect the variability among individual sites.

*Operating Speed Reduction*

It is hypothesized that accident rate increases as operating speed reduction between the approach tangent and the curve increases. The operating speed analysis also compared the four speed estimation equations to evaluate which may be more appropriate to apply in practice. A speed-profile model was used to estimate operating speed reductions (*1*).

All curve sites with no speed reduction ($\Delta V_{85} \leq 0.0$) were included in a single category, and the remaining sites were divided into groups of approximately fifty. Estimated speed reductions ranged from 0 to 30 km/h. A mean speed reduction and mean accident rate was calculated for each group of sites. The model form in equation 5 was analyzed.

Table 1 summarizes the regression results, which verify previous research indicating that operating speed reduction is a strong predictor of accident rates on curves (*1*). Speed estimation equations 1 and 4 produced the best-fitting models.

*Superelevation Deficiency*

Four previous studies (*2-4*, *21*) examined superelevation deficiency (or error) as a potential accident surrogate, and three (*2-4*) found statistically significant relationships between accident rates and superelevation deficiency. It was hypothesized that as the deficiency between actual and "optimum" superelevation rate increases, accident experience would increase. The point in question is how "optimum" superelevation is defined.

This research tested four different speed assumptions:

- Faithfully implementing the AASHTO design-speed concept, such that the minimum design speed of any curve along the roadway defined the design speed of the roadway, at which operating speeds are assumed to be fixed.
- Designing superelevation for 97 km/h, which was theaverage of the 85th percentile operating speed on thelong tangents in the speed-geometry data base (*1*). This approach is closely related to the design consistency concept that an alignment should be designed to fit the desired speed of most drivers.
- Using the estimated 85th percentile speed at the midpoint of the curve (as in Australia and Germany), given by each of the four speed estimation equations.
- Basing the optimum superelevation on the estimated maximum 85th percentile speed on the approach tangent using a speed profile model with each speed estimation equation. This approach was used to determine if the consistency concept in its strictest interpretation might be an appropriate method for alignment design.

For each assumed speed, the "optimum" superelevation rate was calculated using the AASHTO method for determining superelevation rates. For curves sharper than appropriate for the assumed speed (based upon an AASHTO recommended maximum superelevation rate of 0.08), the superelevation rate was calculated based on the maximum side friction factor. This method resulted in superelevation rates as high as 0.60 for sharp curves with high assumed speeds.

**TABLE 1 Summary of Operating Speed Reduction Analysis Results**

| Curve Speed Estimation Model | Parameter Estimate | | $R^2$ | MSE (km/h) |
|---|---|---|---|---|
| | $b_0$ | $b_1$ | | |
| Equation 1: R | -2.136 | 0.029 | 0.91 | 0.0078 |
| Equation 2: R, e | -2.049 | 0.036 | 0.74 | 0.0234 |
| Equation 3: R, L, Δ | -2.073 | 0.028 | 0.72 | 0.0264 |
| Equation 4: R, L, Δ, e | -2.064 | 0.029 | 0.83 | 0.0128 |

To provide a common basis for the comparison of each speed assumption, curve sites were divided into eight groups based upon their radius. For each speed assumption, the mean superelevation deficiency for a group of curve sites was regressed against the mean accident rate using the model form in equation 5. The relative explanatory power (based on $R^2$ and root MSE) of superelevation deficiency based upon the four speed assumptions should indicate the relative merits of the speed assumptions (i.e., their reasonableness with respect to actual driver speed behavior and, therefore, their appropriateness for use in design).

Table 2 summarizes the analysis results. Superelevation deficiency based upon the 85th percentile speed on the curve produced the best results, followed by 85th percentile speed on the approach tangent, and 97 km/h design speed. Superelevation deficiency based upon the AASHTO method was not statistically significant.

The finding that 85th percentile speed on the curve produced better results than estimates of 85th percentile speeds approaching the curve may indicate that it is appropriate to assume drivers expect and can be relied upon to reduce their speed on sharper curves. The results support the practice in Germany and other countries to base superelevation rates on the 85th percentile speed on curves, if it is higher than the design speed. It also supports guidelines which allow for some speed reduction on curves (*22-23*). It further suggests that basing superelevation on 85th percentile approach speeds to curves, may be unnecessarily conservative (*24*). The finding that superelevation deficiency based on the current AASHTO method was not a statistically significant predictor of accident rates can be attributed to the method's unrealistic assumptions about driver speed behavior.

*Implied Side Friction Demand*

Implied side friction demand has advantages over the other accident surrogate measures in this analysis. It is based upon the actual radius or degree of curvature and superelevation rate:

$$f_s = \frac{V_{85}^2}{127\ R} - e \qquad (eq.\ 7)$$

where $f_s$ = implied side friction factor, $V_{85}$ = estimated 85th percentile operating speed (km/h), R = actual curve radius (m), and e = actual superelevation rate (m/m).

Since the only estimated value in the calculation is speed, using the implied side friction factor is a direct way to test different speed assumptions. The hypothesis is that accident rate increases as the implied side friction demand increases, as found in previous research (*25*).

From the superelevation deficiency analysis, it was concluded that the two most appropriate speeds used for design may be the 85th percentile operating speed on the curve and the maximum 85th percentile operating speed on the approach tangent. This analysis incorporates both the 85th percentile curve and approach speeds estimated by each of the four speed estimation equations. It was expected that the most appropriate speed assumption could be inferred from the strength of the relationships between implied side friction demand and accident rates.

The implied side friction demand was calculated for each site, using the actual radius and measured superelevation on the curve, based upon the estimated operating speed calculated using the speed estimation equations for curve speeds and using the speed profile model for the maximum approach speeds. The implied side friction was calculated for each site, sites were grouped into 10th percentile increments, and mean implied side friction and mean accident rates were calculated for each group. The model form of the regression analysis was as defined in equation 5.

**TABLE 2 Summary of Superelevation Deficiency Analysis Results**

| Deficiency Based On: | $R^2$ | MSE | p-value |
|---|---|---|---|
| AASHTO Method (Min. $V_D$ on Roadway Controls) | 0.04 | 0.13 | 0.64 |
| 96.6 km/h (60 mi/h) Design Speed on all Curves | 0.56 | 0.06 | 0.034 |
| 85th Percentile Speed on Curve (using eq. 1) | 0.82 | 0.02 | 0.0018 |
| 85th Percentile Speed on Curve (using eq. 2) | 0.84 | 0.02 | 0.0013 |
| 85th Percentile Speed on Curve (using eq. 3) | 0.79 | 0.03 | 0.0032 |
| 85th Percentile Speed on Curve (using eq. 4) | 0.81 | 0.03 | 0.0023 |
| Max. 85th Percentile Speed on Approach (using eq. 1) | 0.67 | 0.04 | 0.013 |
| Max. 85th Percentile Speed on Approach (using eq. 2) | 0.67 | 0.04 | 0.014 |
| Max. 85th Percentile Speed on Approach (using eq. 3) | 0.67 | 0.04 | 0.014 |
| Max. 85th Percentile Speed on Approach (using eq. 4) | 0.66 | 0.05 | 0.014 |

Table 3 summarizes the regression results. The results support the hypothesized relationship between mean implied side friction and mean accident rates. The side friction estimates based on estimated 85th percentile curve speeds were generally stronger predictors of accident rates than those based upon the maximum 85th percentile speed on the approach tangent, which is similar to the result for superelevation deficiency.

*Comparison of the Accident Surrogate Measures and Speed Estimation Equations*

To compare the explanatory power of the four accident surrogate measures, all measures were analyzed by using groupings of curve sites based upon each measure. The analysis showed that each measure was statistically significant with each grouping. Overall, the ranking of the strength of the measures was as follows:

- Implied side friction demand based on the 85th percentile speed on the curve.
- Radius or degree of curvature.
- Implied side friction based upon the maximum 85th percentile speed on the approach tangent.
- Operating speed reduction from the approach tangent to the midpoint of the curve.

The four speed estimation equations (eq. 1 through 4) appeared to be approximately equally effective. Comparing Tables 1 through 3 indicates that none of the equations yielded consistently better results across the three surrogate measures that used them.

## CONCLUSIONS

Current U.S. horizontal curve design policy uses the distribution of superelevation as the basis for providing a consistent alignment. However, flaws in the method may contribute to operating speed inconsistencies and observed disparities between design and operating speeds.

This study evaluated the effects of superelevation rate on 85th percentile operating speeds on curves. It is concluded that superelevation rate is statistically significant, but it adds only 1-2 percentage points to the explanatory power ($R^2$) of regression equations including radius or degree of curvature. This marginal improvement in speed estimation did not translate into consistently better explanatory power of accident surrogate measures based upon speed estimates.

This study also evaluated four surrogate measures for accident rates on horizontal curves: radius or degree of curvature, operating speed reduction, superelevation deficiency, and implied side friction factor. All four variables were statistically significant. Implied side friction demand is the most comprehensive measure and produced the best results. Superelevation deficiencies and implied side friction demand based upon the 85th percentile speed on the curve produced better results than those based upon other speed assumptions.

**TABLE 3 Summary of Implied Side Friction Analysis Results**

| Independent Variable | Parameter Estimate | | $R^2$ | MSE | p-value |
|---|---|---|---|---|---|
| | $b_0$ | $b_1$ | | | |
| 85th Percentile Speed on Curve (eq.1) | -2.278 | 2.717 | 0.95 | 0.004 | 0.0001 |
| 85th Percentile Speed on Curve (eq. 2) | -2.284 | 2.868 | 0.79 | 0.018 | 0.0005 |
| 85th Percentile Speed on Curve (eq. 3) | -2.277 | 2.699 | 0.93 | 0.006 | 0.0001 |
| 85th Percentile Speed on Curve (eq. 4) | -2.312 | 2.939 | 0.98 | 0.001 | 0.0001 |
| Max. 85th Percentile Approach Speed (eq. 1) | -2.187 | 1.537 | 0.89 | 0.009 | 0.0001 |
| Max. 85th Percentile Approach Speed (eq. 2) | -2.183 | 1.497 | 0.90 | 0.008 | 0.0001 |
| Max. 85th Percentile Approach Speed (eq. 3) | -2.189 | 1.542 | 0.91 | 0.007 | 0.0001 |
| Max. 85th Percentile Approach Speed (eq. 4) | -2.184 | 1.513 | 0.85 | 0.013 | 0.0001 |

## RECOMMENDATIONS

Several recommendations about U.S. horizontal alignment design follow logically from the results and conclusions of this study. Both the speed and accident analyses provide empirical evidence that reinforces concerns about current U.S. design policy for rural highways.

It is recommended that the United States follow the lead of several other countries by incorporating a feedback loop in rural horizontal alignment design to check for and address operating speed inconsistencies. The strength of operating speed reduction as an accident surrogate measures supports this recommendation.

It is recommended that the United States incorporate consideration of 85th percentile speeds on curves into low-design-speed rural horizontal alignment design. The method may be similar to the procedures used in Germany and Australia, wherein the estimated 85th percentile speed on the curve is used as the basis for superelevation design. The accident analyses involving superelevation deficiency and implied side friction demand, in which use of the estimated 85th percentile speed on the curve yielded the highest explanatory power, support this recommendation.

A simple-linear regression equation (eq. 1) appears to be sufficient for developing speed profiles for operating speed consistency checks in initial alignment design. A multiple-linear regression equation (eq. 3 or 4) might add useful precision in computing speed profiles on existing roadways and for final consistency checks on new designs.

Further research is needed to determine whether operating speed reduction thresholds exist where accident rates significantly differ. If so, appropriate ranges of operating speed reduction should be identified in alignment design policy. Additional research is also needed to determine appropriate side friction factors for design. The accident analysis of implied side friction demand provides some of the necessary information, but also needed is up-to-date information on available friction supply and driver comfort levels with modern vehicles.

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