SPEED VARIABILITY ON RURAL TWO-LANE HIGHWAYS

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ABSTRACT

A better understanding of speed variance on rural two-lane highways may assist in addressing driver error associated with highway geometric elements. Previous research suggests that a relationship exists between speed variance and accident potential. Speed variance increases are associated with an increase in accidents. Therefore, identifying relationships between speed distribution measures (i.e., mean speed, speed variance, coefficient of variation) of free-flowing vehicles and roadway characteristics may identify inconsistent roadway features.

Speed data were collected at the midpoint of the preceding tangent and the curve for 155 horizontal and vertical curves from four geographic regions. Four hypotheses were explored to determine if relationships between speed statistics and geometry could be used to identify design inconsistencies. Statistical tests were conducted to identify relationships between mean speed, speed variance (standard deviation), and roadway characteristics for tangents, horizontal curves, and vertical curves. The findings suggest that speed distribution measures do not appear useful in the evaluation of design consistency.

Keywords: Design Consistency, Two-lane Roads, Speed Variance, Speed Standard Deviation

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BACKGROUND

Consistency in speed is an important safety concern on two-lane rural highways. The Federal Highway Administration (FHWA) (*1,2*) is developing an Interactive Highway Safety Design Model (IHSDM) to evaluate design consistency. Currently the model uses 85th percentile speed prediction; however, inclusion of other mehods may identify additional design inconsistencies. Analysis of relationships between speed variability and geometry may be a potential approach to characterize inconsistent locations.

Free-flow speeds depend on the drivers' perception of the roadway conditions, environment, and geometry. Thus, free-flow speeds and the statistical measures associated with them may identify alinement deficiencies. A common hypothesis in traffic flow theory is that speeds, particularly of free-flowing vehicles, are normally distributed (*3*). It is believed that vehicle speeds on roadways follow a normal distribution and that distribution measures could identify geometric deficiencies.

The purpose of this research was to identify the relationship between rural two-lane highway geometry and speed variability. Locations with geometric features exhibiting higher values of speed variability may be locations associated with driver error. Significant changes in speed distribution measures may suggest that design inconsistencies are present between alinement features. One basis for using descriptive speed statistics originates from the idea that "speed variance, not speed magnitude, is the issue" (*4*).

Statistical Measures and Accident Potential

Previous research has made observations regarding speed variability, focusing on the relationship between statistical measures and accident potential. Traditionally, higher speed variability suggests higher accident potential. "The weight of evidence would lead to the conclusion that speed variance and accident frequency are directly related. The greater the absolute deviation from mean traffic speed, the higher the accident rate"(*5*). A recent review of the safety effects of the 55 mph (88.5 km/h) National Maximum Speed Limit reached a similar conclusion: "A wide variability in speeds increases the probability of accident occurrence" (*6*).

A 1988 study by Garber and Gadiraju (*7*) related speed variance and accident experience. The study examined 36 roadway segments in Virginia, including interstates, arterials, and major collectors. The analysis compared accident data from 1983 through 1986 to four different speed measures: design speed, posted speed, and the mean and variance of operating speeds. The mean speed and speed variance were computed from individual vehicle speeds measured using automatic traffic data recorders for continuous 24-hour weekday periods. Their results compared the effects of traffic and geometry on vehicle speeds, indicating that the speeds were not free-flow. Conclusions from their research were (*7*):

- Accident rates increase with increasing speed variance for all road classes.
- Speed variance on a highway segment tends to be minimum when the difference between design and posted speed is between 8 and 16 km/h (5 and 10 mph).
- For average speeds between 40 and 112.5 km/h (25 and 70 mph), speed variance decreases with increasing average speed.
- The difference between design speed and posted speed has a significant effect on speed variance.

However, this study found differences in speed variance between distinct roadways rather than differences in speed variability between features along a given roadway.

Solomon (*8*) and Cirillo (*9*) used accident-involved vehicles on two- and four-lane rural highways and interstates as their unit of analyses. Their studies estimated the incremental deviation from the mean speed of the accident-involved vehicle's speed. Both studies found that the lowest accident rate occurred within a speed range 15 to 20 percent higher than the mean speed. As deviation increased above this range, accident involvement rates increased for vehicles traveling at speeds either higher or lower than the mean speed. Neither study identified the observations as being free-flow speed.

Lindeman and Ranft (*10*) analyzed geometry effects on speed distribution measures at the horizontal curve midpoint. Their research focused on speed standard deviation for curves with radii from 32.5 to 1000 m. Their findings suggest that standard deviation increases as curve radius increases for small radius curves and remains constant for larger radius curves. The following equation was developed to predict the relationship between standard deviation and mean speed (*10*):

$$s = 0.14 \times V_M \qquad (1)$$

where:

s = standard deviation (km/h); and
V_M = mean speed, $30 < V_M < 95$ km/h.

RESEARCH HYPOTHESES

The relationships between speed distribution measures and alinement were explored in a FHWA project (*2*). It is hypothesized that high speed variance identifies inconsistent design features, whereas consistent features result in low speed variance (see Figure 1). If a relationship exists, a model could be developed to predict speed variance of passenger vehicles based on roadway geometry. The model could serve as a design consistency method. Hypotheses considered within this study include:

Hypothesis One:	Speed distribution measures are related to geometry.
Hypothesis Two:	Design and/or posted speed can be used to predict speed variance.
Hypothesis Three:	The relationship between successive features can be used to predict speed variance.
Hypothesis Four:	Increased speed variance can be used as an indicator of design inconsistency.

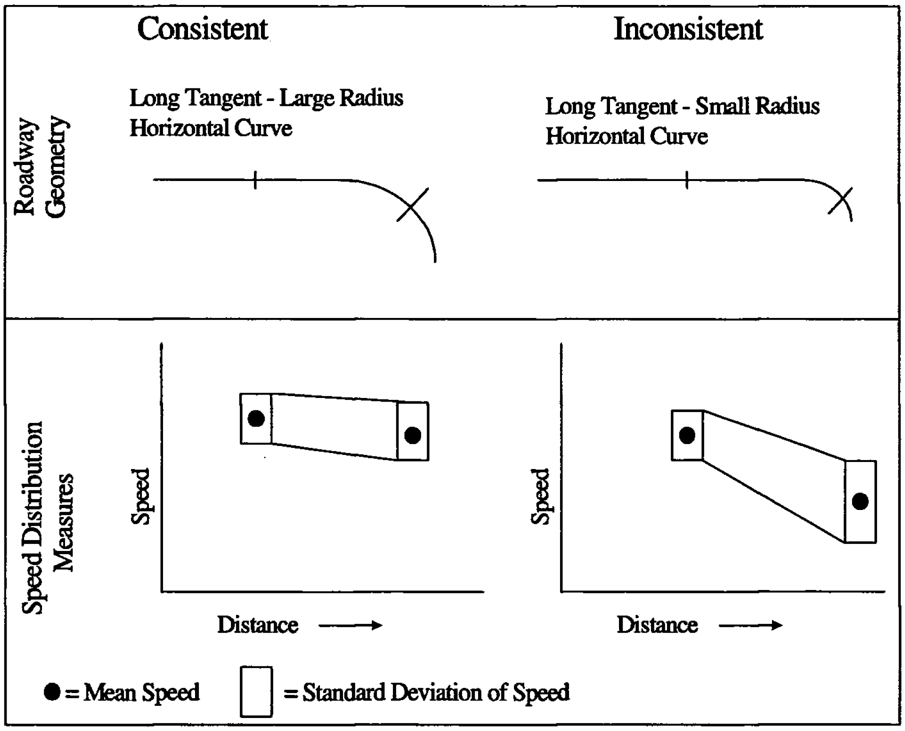

Figure 1. Hypothesized Relationship of Roadway Geometry and Standard Deviation of Speed.

The first hypothesis assumes that horizontal and vertical design features can predict sample speed distribution measures. It is hypothesized that restrictive roadway features cause large variations in speed; whereas, forgiving features allow for a consistent range of operating speeds, resulting in uniform, lower speed variability.

The second hypothesis suggests that distribution measures vary with design and/or posted speed. Garber's (7) findings suggested that posted speed is related to operating speeds, and design speed is related to the consistency of an individual alinement feature with respect to the overall road section.

The third hypothesis states that speed distribution measures are associated with drivers' perception of alinement changes. Speed distributions are constantly changing from feature to feature, with the relationship being dependent upon the change.

The fourth hypothesis suggests that speed variance can be used to identify inconsistent design features. High values of speed variance have been associated with high accident potential. This relationship may be related to the geometry of the roadway.

SPEED DATA

Speed data were collected at 155 study locations for a minimum of 100 free-flow vehicles using radar devices or on-pavement piezoelectric sensors at the tangent and curve midpoints (*1*). The 155 study locations were distributed across four regions: Washington and Oregon (West), Texas (South), Pennsylvania and New York (East), and Minnesota (Midwest). Data were collected under daytime, dry pavement conditions. Speed statistics for each site were drawn from free-flow vehicles using the same population of drivers at the tangent and neighboring curve. Table 1 lists the site selection criteria.

Table 1. Site Selection Criteria (*1*).

Control	Criteria
Area Type	Rural
Density of Access	≤ 3 per km
Points	Collector or minor arterial
Functional	≤ 120 km/h
Classification	75 km/h - 115 km/h
Design Speed	80 m - 3500 m
Posted Speed Limit	-10% to +10%
Radii	500 - 4000 vehicles per day
Grade	2.74 - 3.66 m
Traffic Volumes	No restriction
Lane Widths	≥ 60 m
Horizontal Curve	Type I or II (as defined by
Length	AASHTO)
Vertical Curve Length	
Vertical Curve	

HYPOTHESIS ONE: GEOMETRY EFFECTS

Evaluation of correlation matrices and graphical plots identified relationships and interactions between variables. Pearson correlation coefficients were calculated between mean speed, speed standard deviation, coefficient of variation and the following independent geometric variables:

- tangent length
- curve radius
- curve length
- superelevation
- deflection angle
- grade
- lane width
- pavement width
- curvature rate
- vertical curve length
- approach grade
- departure grade

The hypothesis that alinement affects statistical measures could be validated if mean speeds were significantly different between the tangent midpoint and the following horizontal or vertical curve. Although higher mean speed values were observed on the tangent, no significant differences existed in mean speed or standard deviation values between the locations.

Mean speed values ranged from 45 to 114 km/h. The standard deviation of most sites varied between 5 and 14 km/h (see Figure 2). Potential outliers within the data set had standard deviations greater than 16 km/h. Figure 2 illustrates that as mean speed increased, more variation within standard deviations of the speed measurements occurred.

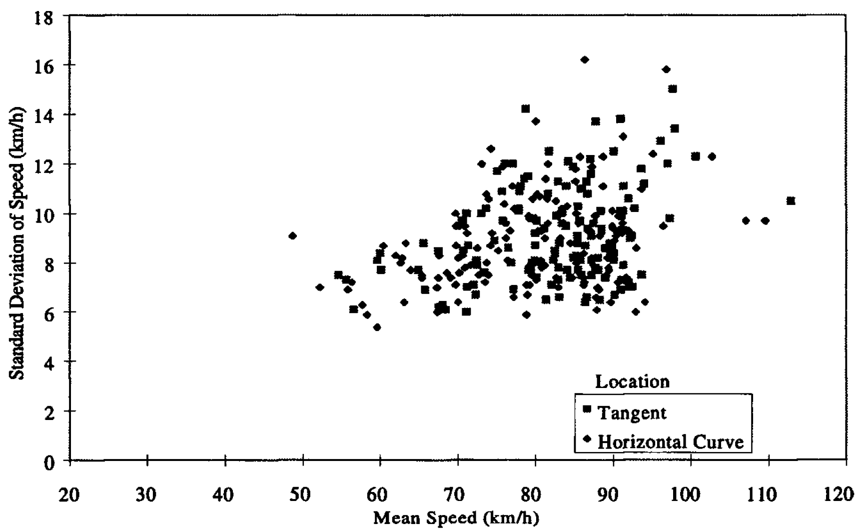

Figure 2. Standard Deviation of Speed versus Mean Speed on Tangents and Horizontal Curves.

Horizontal Curves

Speed standard deviation for the horizontal curve study sites is shown in Figure 3. No significant difference in standard deviation was found with respect to grade, but the figure shows that for six small radii sites (i.e., less than 100 meters), standard deviation was low which could be a result of the lower speeds observed at the lower radii values (i.e., lower mean speeds lead to lower standard deviations). As radii increased, geometric controls decreased and the range of standard deviation increased, suggesting rejection of Hypothesis One.

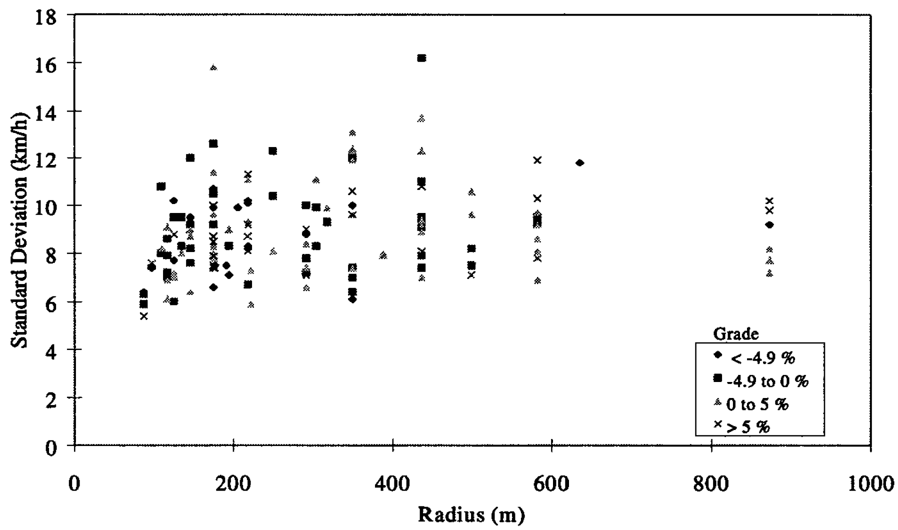

Figure 3. Horizontal Curve Speed Standard Deviation versus Radius.

The poor relationships found through the correlation analysis and plots suggested that transformations of independent variables might be more appropriate. The transformations included: the inverse of the radius, the square root of the radius, the log of radius, and radius squared. Other transformations of independent variables yielded no significant findings.

Figure 4 shows standard deviation versus inverse radius (1/R). Generally as 1/R increases (i.e., radius decreases), the range of the standard deviations decreases. This observation may only be valid for this data set because of the small number of sites with 1/R above 0.008 ®_<125 m). Two outliers were observed at 0.002 and 0.006. Aside from these two points, speed standard deviation was consistently between 5 and 14 km/h.

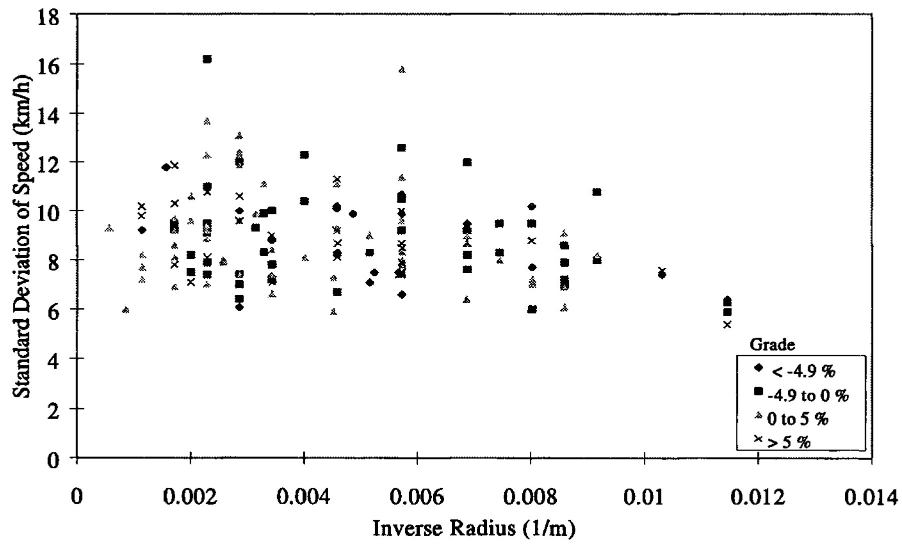

Figure 4. Horizontal Curve Speed Standard Deviation versus Inverse Radius.

This relationship implies that the horizontal curve radius controls speed variance when the radius is below 100 meters. It appears that, for horizontal curves with radii smaller than 100 meters, higher-speed drivers entering the curve reduce their speeds more than lower-speed drivers. For the six study locations with curve radii less than 100 meters, this greater reduction in speed by higher-speed drivers resulted in a decrease in standard deviation.

Vertical Curves

The rate of curvature (K), vertical curve length, approach grade, and departure grade were considered as possible independent variables. Figure 5 illustrates the plot of standard deviation by rate of curvature for crest vertical curves. The figure separates study sites based on the K-values. Non-Limited Sight Distance curves have K-values greater than 43. Limited Sight Distance (LSD) curves have K-values less than 43. No significant findings were apparent in Figure 5.

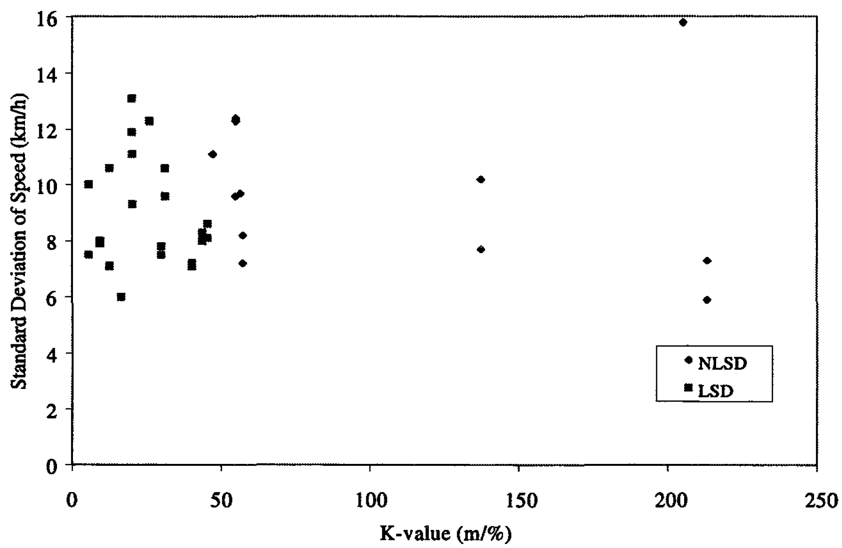

Figure 5. Standard Deviation of Speed versus Rate of Curvature for Crest Vertical Curves.

HYPOTHESIS TWO: DESIGN AND/OR POSTED SPEED EFFECTS

In the preliminary analyses several methods were used to identify possible relationships between independent geometric variables and statistical speed parameters. Results suggested no relationships between geometric elements and speed distribution measures with one exception-radii smaller than 100 meters result in smaller standard deviations as compared to larger radii curve.

Garber and Gadiraju (*7*) found that speed variance is at a minimum when the difference between design speed and posted speed is between 8 and 16 km/h. Their findings prompted inclusion of the second hypothesis. Inferred design speed for the data was calculated from measured superelevation rates and the radius. Posted speeds were recorded during data collection for each site. Advisory speed limits were not considered since previous research shows they do not affect the operating speed of drivers (*11*).

Inferred design speed was compared to standard deviation with no clear trends in the data set (Figure 6). As the figure shows, there is large variation in speed standard deviation for design speeds in excess of 70 km/h. The smaller range of speed standard deviations for the lower design speeds may be a function of the design speeds but the results are inconclusive for the low number of data points.

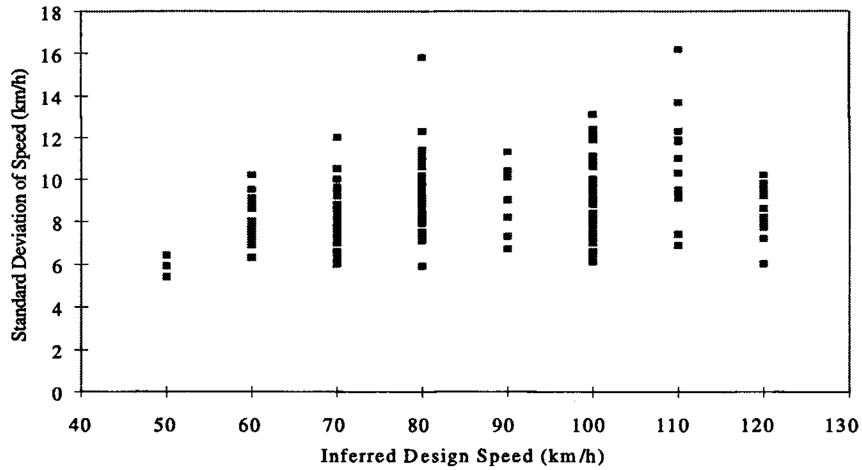

Figure 6. Standard Deviation of Speed versus Inferred Design Speed for Horizontal Curve Sites.

Comparisons with posted speed showed that higher speed limits generally result in higher standard deviations (Figure 7). These higher standard deviations follow the trend illustrated in Figure 2, higher standard deviations are associated with higher speeds. This finding corresponded to the results of Lindeman and Ranft (*10*).

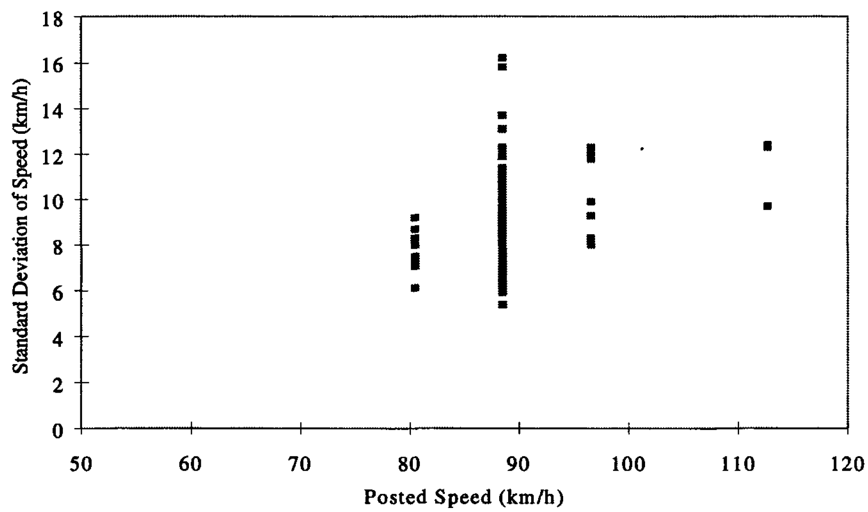

Figure 7. Standard Deviation of Speed versus Posted Speed Limit for All Sites.

The effect of the difference between design and posted speed on speed variance was also examined. Garber and Gadiraju (7) suggest that the difference between these two speeds showed a quadratic relationship against the speed variance. Initial plots of the data did not support this result (Figure 8). It was hypothesized, based on findings from Garber and Gadiraju, that if the difference between the design and the posted speed was high, design inconsistencies would exist. Initial analysis suggested that no relationship could be found.

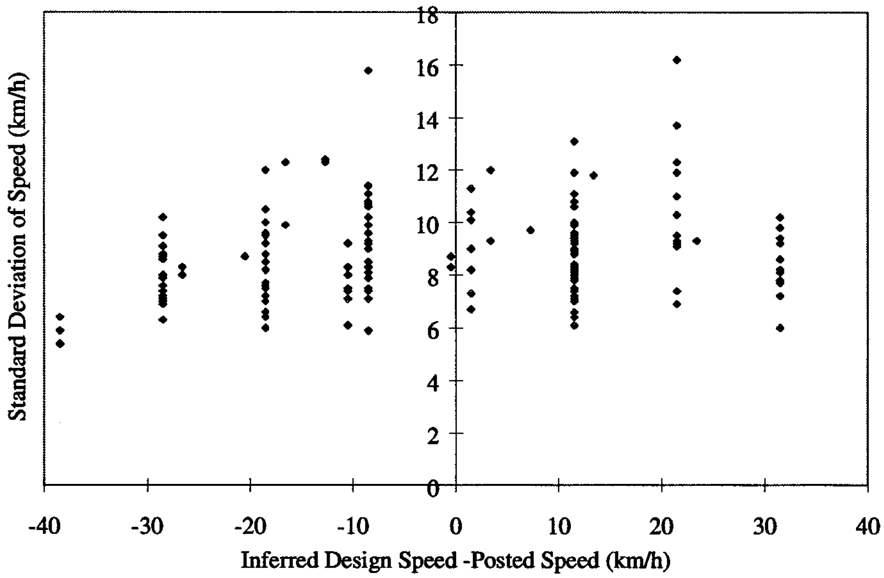

Figure 8. Standard Deviation of Speed versus Difference Between Inferred Design Speed and Posted Speed.

Revision to this approach involved determination of differences where the posted speed was higher than inferred design speed. Radius and pavement width were significantly related to standard deviation for the reduced data set (72 horizontal curves). Figure 9 shows the relationship. The following regression model was developed:

$$s = 15.8 - \frac{517.2}{R} - 0.4 \times (PW) \qquad (2)$$

where:

s = standard deviation (km/h);
R = radius (m); and
PW = pavement width (m).

The coefficient of determination (r^2) for the model containing radius and pavement width was 54 percent and Mallow's C_p was 3.7. The coefficients for 1/R and PW were found significant at the 0.0001 level for 72 horizontal curves where posted speed exceeded design speed. Equation 2 shows that speed standard deviation decreases with increasing pavement width (by 0.4 km/h for every 1 m increase in pavement width) and increases with increasing radius.

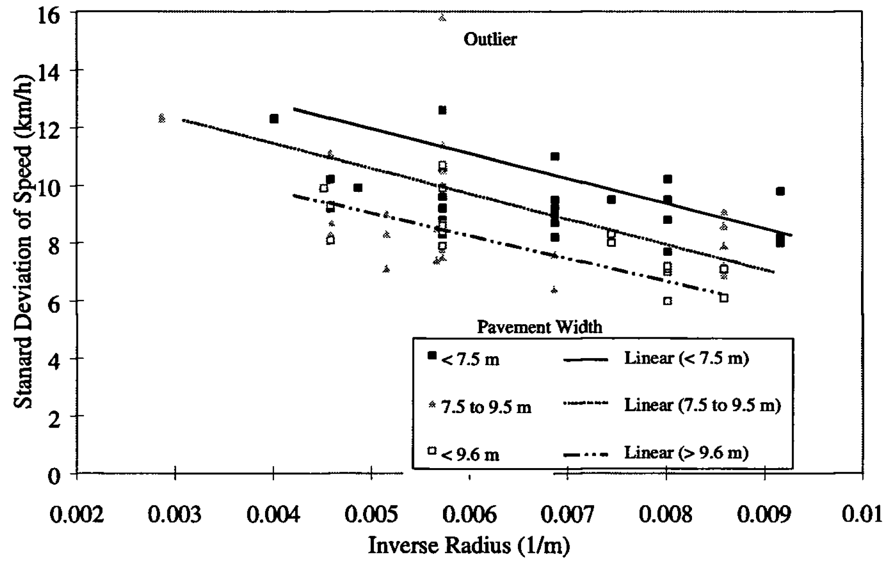

Figure 9. Standard Deviation of Speed versus Inverse Radius for Sites with Inferred Design Speed Below Posted Speed.

HYPOTHESIS THREE: PRECEDING FEATURE EFFECT

The behavior of the speed distributions at the curve followed the tangent speed distribution measures. Thus, if there was high variability in the sample speeds at the tangent midpoint, then there was high variability at the curve midpoint. Figure 10 compares the coefficient of variation for the tangent and the horizontal curve. The figure illustrates a linear relationship; however, the slope does not equal one. This relationship is not unexpected since the same population of drivers was measured at both tangent and curve locations.

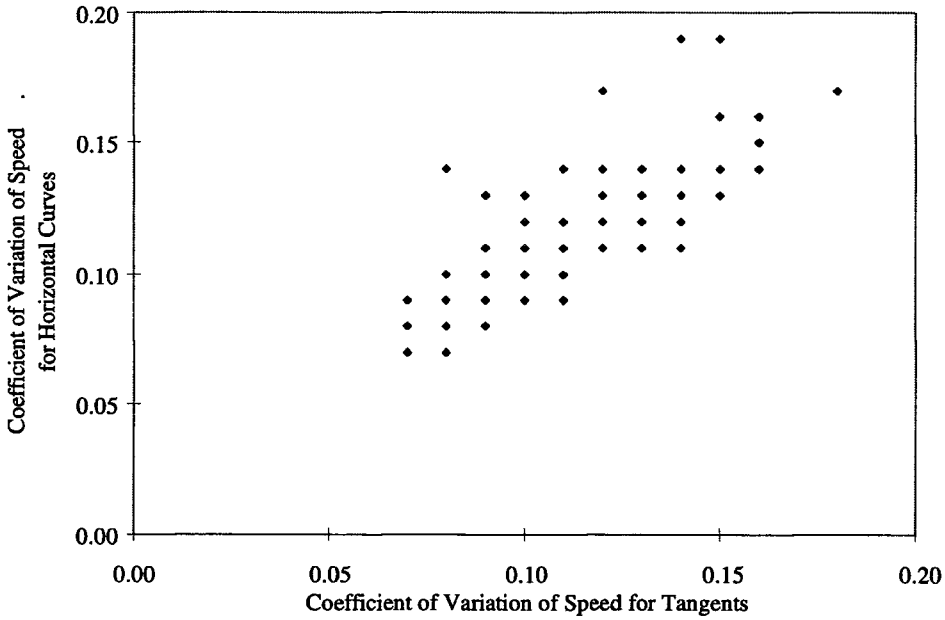

Figure 10. Coefficient of Variation of Speed for Horizontal Curves versus Coefficient of Variation of Speed for Tangents.

HYPOTHESIS FOUR: SPEED STATISTICS AS DESIGN CONSISTENCY MEASURE

The fourth hypothesis is that speed standard deviation can be used as an indication of the presence of a design inconsistency. Figure 1 hypothesizes that as the radius of a horizontal curve decreases, speed standard deviation will increase. Some specified increase in standard deviation could then be used to identify particular horizontal curves as being inconsistent.

The data do not support this hypothesis. A key observation from the data is that standard deviation (average over all sites) is lower on horizontal curves (8.9 km/h) than on tangents (9.2 km/h). This finding is opposite to the fourth hypothesis, although the observed difference was not statistically significant.

Further investigations were undertaken using regression analysis to evaluate relationships between speed measures and geometry. These analyses used the comparable speed measures for the preceding tangent to normalize the speed measures for each horizontal curve. These two sets of analyses (referred to as unnormalized and normalized speed data) are presented below.

Unnormalized Speed Data

Only horizontal curves in level terrain or on constant grades were considered (i.e., combinations of horizontal and vertical curvature were excluded) in an evaluation of the effect of horizontal curvature on speed variance and other statistics. A total of 95 curves were available. At each horizontal curve, speed data (mean, standard deviation, variance, and 85^{th} percentile) were provided separately for each of nine vehicle types. Similar speed data were also available for the tangent roadway upstream of each horizontal curve These speed statistics were weighted by the number of vehicles in each vehicle category (nine types of vehicles) and pooled into a single "all-vehicle type" category. These pooled speed statistics were used in the statistical analyses.

Each curve was described by the following parameters—independent variables:

- Curve radius (m); three functional forms of the curve radius were used in all the models: R, 1/R, and $R^{0.5}$
- Grade (percent)
- Deflection angle (degree)

The speed statistics in the raw database were associated with either the tangent or the curve. These statistics were called "unnormalized speed statistics" and used as dependent variables for modeling.

Prior to the regression analyses, many two-variable plots were drawn to assess the form of potential relationships between variables. Single-variable models and multiple-variable models were then developed. Based on these plots, linear regression models were developed between curve speed statistics and various geometric features. In a few instances, based on residual plots, an additional term representing the square of the curve radius (R^2) was added to selected models.

The findings of the regression analyses from unnormalized speed statistics were as follows:

- No relationships of practical importance were found between curve speed variance statistics (expressed as variance, standard deviation, or coefficient of variation) and tangent speed variance statistics and/or curve geometries.

- Of all the models relating various curve speed statistics to tangent speed statistics and/or curve geometries, only those models using either the $(\text{mean speed})_{curve}$ or the $(85^{th}\text{ percentile speed})_{curve}$ as the dependent variable indicated a significant relationship of practical importance (r^2 above 30 percent) with the corresponding tangent speed statistics and/or curve geometry.

- Generally, models including 1/R yielded slightly higher r^2-values than models including $R^{0.5}$. Either of these two forms of radius yielded considerably higher r^2-values than the radius.

- No significant improvement in the fit of the curve mean speed and 85th percentile speed models was obtained when including grade and deflection angle in addition to the corresponding tangent speed statistics combined with either 1/R or $R^{0.5}$.

- For selected models including R^2 in addition to combinations of 1/R, $R^{0.5}$, grade, and/or deflection angle, no significant improvement in model fit was obtained compared with the models without R^2.

- In summary, simple linear models relating (mean speed or 85th percentile speed)$_{curve}$ to (mean speed or 85th percentile speed)$_{tangent}$ in addition to either 1/R or $R^{0.5}$, provided the best relationships.

Normalized Speed Data

Normalized speed statistics were created for each horizontal curves adjusting for the speed measures obtained on the preceding tangent. The following normalized speed statistics were obtained:

1. Mean speed reduction = (mean speed)$_{tangent}$ - (mean speed)$_{curve}$ in km/h
2. Log(mean speed reduction + 10 km/h), (a shift of 10 km/h was made to adjust for negative reductions)
3. Percent mean speed reduction = [mean speed)$_{tangent}$ - (mean speed)$_{curve}$]/(mean speed)$_{tangent}$ in percent.
4. Log(percent mean speed reduction + 10%), (a shift of 10% was made to adjust for negative percent reductions)
5. 85th-percentile speed reduction = (85th-percentile speed)$_{tangent}$ - (85th-percentile speed)$_{curve}$ in km/h
6. log(85th-percentile speed reduction + 10 km/h), in km/h (a shift of 10 km/h was made to adjust for negative reductions)
7. Speed variance reduction = (speed variance)$_{tangent}$ - (speed variance)$_{curve}$ in $(km/h)^2$
8. Speed standard deviation reduction = (speed standard deviation)$_{tangent}$ - (speed standard deviation)$_{curve}$ in km/h
9. Speed coefficient of variation reduction = (speed coefficient of variation)$_{tangent}$ - (speed coefficient of variation)$_{curve}$ (unitless)
10. Speed standard deviation ratio = (speed standard deviation)$_{tangent}$/(speed standard deviation)$_{curve}$ (unitless)

These normalized speed statistics were used as dependent variables for modeling. These pairwise speed measure differences between a horizontal curve and its preceding tangent provide a more appropriate statistical approach for determining the geometry effects on speed measures than the two-sample tests presented earlier.

Single-variable models and multiple-variable models were developed to model the normalized speed variables identified as a function of only geometric parameters of the curve (i.e., radius, deflection angle, and grade).

The findings of the regressional analysis for the normalized data were as follows:

- Overall, mean speeds are generally lower on horizontal curves than on the preceding tangents. On average, mean vehicle speed on the horizontal curve was 2.8 km/h lower than on the preceding tangent; the speed variance was 9.5 percent lower on the curve than on the preceding tangent. These differences were statistically significant at the 5 percent significance level.

- Generally, no statistically significant regression models related any of the normalized speed variance measures listed above to curve geometry.

- Models in which any of the form of normalized mean speeds or 85th percentile speeds shown above was modeled as a function of curve geometries yielded r^2-values between 14 percent and 34 percent.

- Some of the relationships between forms of normalized mean speeds (or normalized 85th percentile speed) and curve geometry were modeled as exponential decay functions based on plots; however, although significant, these models did not add any new insight to the previous unnormalized models.

- The models relating the (normalized) percent mean speed reduction to either 1/R and grade or to radius, grade, and deflection angle provided the only r^2-values above 30 percent (34 percent and 32 percent, respectively).

DISCUSSION OF RESULTS

The analyses conducted for Hypothesis One found no differences in a variety of speed measures for tangents, horizontal curves, and vertical curves with only one exception- radii smaller than 100 m result in smaller standard deviation. In particular, there was low correlation between geometric features and standard deviation. Thus, the hypothesis that roadway geometry can be used to predict standard deviation does not appear to be supported.

The analyses conducted for Hypothesis Two examined the relationship between speed measures and design or posted speed and did not find significant relationships. Expected trends in the data were found that related speed measures to these two speed components, but the variation of the data suggested that design and posted speeds were not accurate predictors of speed measures. For conditions where the design speed is less than the posted speed, a relationship between standard deviation, radius, and pavement width was found. Standard deviation decreased with decreasing radius and increasing pavement width. This finding is unique to those conditions where posted speed exceeds design speed, or arguably where design inconsistencies exist.

Data analysis for Hypothesis Three suggests correlation between the coefficient of variation on a horizontal curve and on its preceding tangent. Assuming that the curve radii is greater than 100 m, the standard deviation of the curve can be predicted knowing the coefficient of variation on the tangent and the curve mean speed.

The unnormalized and normalized analysis results reported are in conflict with the Hypothesis Four and, therefore, do not support the use of speed variance as a design consistency measure. This evaluation was undertaken to test whether speed variance might be a suitable design consistency measure if speed variance increased at locations with potentially inconsistent designs such as sharp horizontal curves. In fact, as the results presented in this paper indicate, speed variance generally decreased on horizontal curves as compared to the upstream tangent. This finding is consistent with the theory that horizontal curves affect the speeds of faster vehicles more than that of slower vehicles, thus reducing the speed variance.

Given these finding, speed variance does not appear to be appropriate as a design consistency measure.

CONCLUSIONS

The idea that speed variance measures can be used to evaluate geometric design consistency does not appear to be valid. In general, there was low correlation between geometric features and speed variance. In addition, large differences in speed variance existed for the different design and posted speeds. As expected due to sampling the same drivers, there was a relationship between speed distribution measures of successive features. Standard deviation does appear to change between horizontal curves and tangents, but the change is in the direction of lower, rather than higher, speed variance on horizontal curves than on tangents.

These results indicate that speed variance is not an appropriate measure of design consistency for horizontal curves on rural two-lane highways. While an increase in speed variance may be an indicator of potential safety problems for some geometric design features or traffic situations, it is not useful in explaining safety differences between tangents and horizontal curves on two-lane highways.

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