Evaluation of Design Consistency Methods for Two-Lane Rural Highways, Executive Summary

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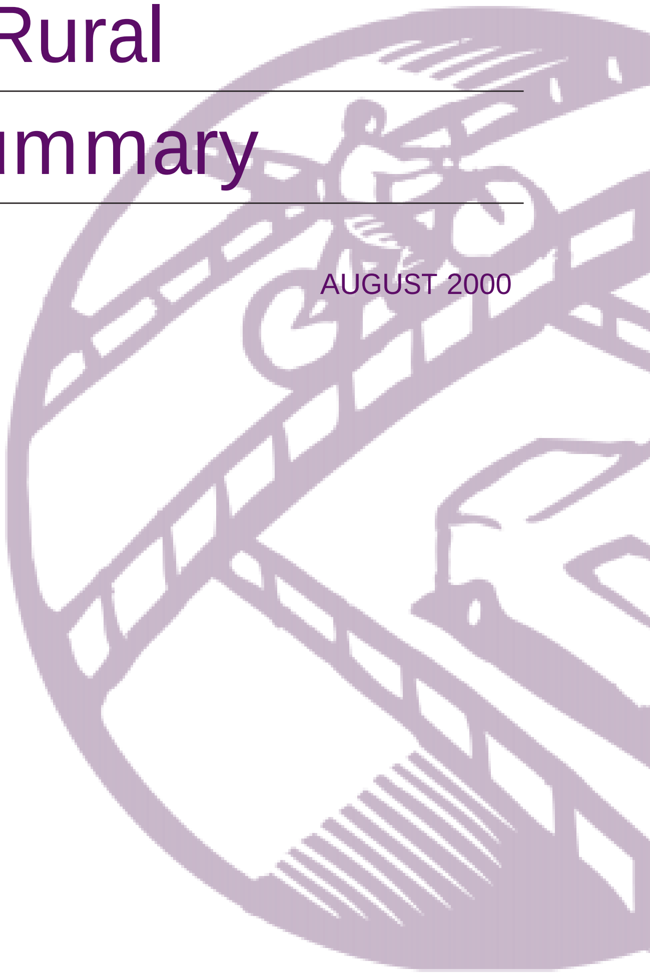

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16. Abstract

Design consistency refers to the conformance of a highway’s geometry with driver expectancy. Techniques to evaluate the consistency of a design documented within this report include speed-profile model, alignment indices, speed distribution measures, and driver workload. The use of operating speed as a consistency tool requires the ability to accurately predict speeds as a function of the roadway geometry. In this research project, several efforts were undertaken to predict operating speed for different conditions such as on horizontal, vertical, and combined curves; on tangent sections using alignment indices; on grades using the TWOPAS model; and prior to or after a horizontal curve. The findings from the different efforts were incorporated into a speed-profile model. Alignment indices are quantitative measures of the general character of a roadway segment’s alignment. These potential indicators may identify a geometric inconsistency when there is a large increase in the magnitude of the alignment indices for a successive roadway segment or feature or when a high rate of change occurs over some roadway length. Speed distribution measures investigated included variance, standard deviation, coefficient of variation, and coefficient of skewness. Driver workload is a measure of the information processing demands imposed by the roadway geometry on a driver.

17. Key Words
Two-lane rural highway, design consistency, IHSDM, speed prediction, speed profile, acceleration/deceleration, alignment indices, speed distribution, driver workload, visual demand.

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FOREWORD

Current procedures for designing rural alignments rely on the selection and application of design speeds. U.S. highway geometric design researchers and practitioners generally recognize the need to supplement current design procedures for two-lane rural highways with reliable, quantitative safety-evaluation methods. To address this need, the Federal Highway Administration is developing the Interactive Highway Safety Design Model (IHSDM) as a framework for an integrated design process that systematically considers both the roadway and the roadside in developing cost-effective highway design alternatives. The focus of IHSDM is on the safety effects of design alternatives. Design consistency is one of several modules which are to be integrated with commercial CAD/roadway design software. Other IHSDM modules include: crash prediction, driver/vehicle, intersection diagnostic review, policy review and traffic analysis.

The research documented in this report provided a speed-profile model that can be incorporated into the design consistency module of IHSDM. The model can be used to evaluate the design consistency of the roadway or can be used to develop a speed profile for an alignment. The model considers both horizontal and vertical curvature and the acceleration or deceleration behavior as a vehicle moves from one feature to another. The research also demonstrated that predicted speed reduction on a horizontal curve relative to the preceding curve or tangent has a strong relationship to accident frequency. In addition, the research investigated alternatives that could be used in the design consistency module of IHSDM. The three methods studied included: alignment indices, spot speed variability measures, and driver workload. Based upon the findings, alignment indices and speed variability measures were not recommended for use in the design consistency module. Driver workload, however, has a good potential as a design consistency rating measure.

Michael F. Trentacoste

Michael F. Trentacoste, Director
Office of Safety Research & Development

NOTICE

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Many individuals contributed to this research. Following are the individuals who contributed to each major effort within the project:

- Principal Investigators (Kay Fitzpatrick and Raymond A. Krammes)
- Predicting Speed on Two-Lane Rural Highways (Nelson Irizarry, Kay Fitzpatrick, Jon M. Collins, Raymond A. Krammes, Karl Passetti, and Karin M. Bauer)
- Vehicle Performance Using TWOPAS (Douglas W. Harwood)
- Acceleration/Deceleration Modeling (Lily Elefteriadou and John McFadden)
- Validation of Speed-Prediction Equations (Lily Elefteriadou and John McFadden)
- Development of Speed-Profile Model (Kay Fitzpatrick and Jon M. Collins)
- Alinement Indices (Kelly D. Parma, Raymond A. Krammes, and Kay Fitzpatrick)
- Relationship of Geometric Design Consistency Measures to Safety (Ingrid B. Anderson, Douglas W. Harwood, Karin M. Bauer, and Kay Fitzpatrick)
- Relationship of the Design Consistency Module to Other IHSDM Components (Douglas W. Harwood)
- Speed Distribution Measures (Jon M. Collins, Karin M. Bauer, Douglas W. Harwood, Kay Fitzpatrick, and Raymond A. Krammes)
- Driver Workload—Field (Mark D. Wooldridge, Rodger Koppa, Karin M. Bauer, Raymond A Krammes, and Kay Fitzpatrick)
- Driver Workload/Eye Fixation—Simulation (Omer Tsimhoni, Paul Green, and Brian Poggioli)
- Comparison of Driver Workload Values (Mark D. Wooldridge and Karin M. Bauer)
- Summary, Findings, Conclusions, and Recommendations (All)

In addition, several students and staff assisted the research efforts in data collection and reduction, and report preparation. We would like to acknowledge the following: Terri Arendale, Anastasia Driskill, Aimee Flannery, Crystal Garza, Kevin Gee, Martin Mangot, John Hawkins, Micah Hershberg, Aaron Hottenstein, Shirley Kalinec, Stacy King, Lizette Laguna, Yingwei Ni, Chris Orosco, Kerry Perrillo, Kelly Quy, Darren Torbic, Jason Vaughn, and Dan Walker. Finally, we would like to acknowledge the assistance of Quinn Brackett of Brackett and Associates for helping frame the driver workload research effort.

BACKGROUND

The goal of transportation is generally stated as the safe and efficient movement of people and goods. To achieve this goal, designers use many tools and techniques. One technique used to improve safety on roadways is to examine the consistency of the design. Design consistency refers to highway geometry's conformance with driver expectancy. Generally, drivers make fewer errors at geometric features that conform with their expectations. An inconsistency in design can be described as a geometric feature or combination of features with unusual or extreme characteristics that drivers may drive in an unsafe manner. This situation could lead to speed errors, inappropriate driving maneuvers, and/or an undesirable level of accidents.

In the United States, design consistency on two-lane rural highways has been assumed to be provided through the selection and application of a design speed. One weakness of the design-speed concept is that it uses the design speed of the most restrictive geometric element within the section, usually a horizontal or vertical curve, as the design speed of the road. Consequently, the design-speed concept currently used in the United States does not explicitly consider the speeds that motorists travel on tangents or less restrictive curves. Other weaknesses in the design-speed concept have generated discussions and additional research into other methods for evaluating design consistency along two-lane rural highways. Both speed-based and non-speed-based highway geometric design consistency evaluation methods have been considered. These methods have taken several forms and can generally be placed in the following areas: vehicle operations-based consistency (including speed), roadway geometrics-based consistency, driver workload, and consistency checklists.

Some of these methods may be incorporated into the Interactive Highway Safety Design Model (IHSDM). IHSDM is being developed by the Federal Highway Administration (FHWA) as a framework for "an integrated design process that systematically considers both the roadway and the roadside in developing cost-effective highway design alternatives."(1) The focus of IHSDM is on the safety effects of design alternatives. Design consistency is one of several modules which are to be integrated with commercial computer-aided design (CAD)/ roadway design software in the current version of IHSDM.(2) Other IHSDM modules include: crash prediction, intersection diagnostic review, roadside safety, driver/vehicle, policy review and traffic analysis.

OBJECTIVES

An earlier FHWA study, *Horizontal Alignment Design Consistency for Rural Two-Lane Highways* (FHWA-RD-94-034), developed a design consistency evaluation procedure that used a speed-profile model based on horizontal alignment.(3) The objective of this study, "*Evaluation of Design Consistency Methods for Two-Lane Rural Highways*" *(FHWA-RD-99-173),* was to expand the research conducted under the previous FHWA study in two directions. These directions were 1) to expand the speed-profile model and 2) to investigate three promising design consistency rating methods.

The previous study's model estimates speeds along a roadway using horizontal alignment data. Recommendations from that study included conducting further research to validate the developed speed-profile model (including the 85th percentile speeds on curves and long tangents) and to validate the assumed rates and locations relative to curves at which acceleration and deceleration actually occurs. To meet these recommendations, the objectives for the current FHWA study were to:

- Develop speed prediction equations for horizontal and vertical alignments and for other vehicle types.
- Determine the effects of spiral transitions on speeds.
- Determine the deceleration and acceleration rates for vehicles approaching and departing horizontal curves.
- Validate the speed prediction equations.
- Develop a speed-profile model for inclusion in IHSDM.
- Identify the relationship of the design consistency module to other modules and components of IHSDM.

While predicting operating speed is the more common method for evaluating the consistency of a roadway, other methods have been discussed and explored. The three methods selected for additional investigation in this study included: alignment indices, speed distribution measures, and driver workload. Alignment indices are quantitative measures of the general character of a roadway segment's alignment. These potential indicators may identify a geometric inconsistency when there is a large increase in the magnitude of the alignment indices for a successive roadway segment or feature or when a high rate of change occurs over some length of road. Speed distribution measures that are candidates for a consistency rating method include variance, standard deviation, coefficient of variation, and coefficient of skewness. Driver workload is a measure of the information processing demands imposed by roadway geometry on a driver. An increase in driver workload is a potential indication that a feature is inconsistent. Following is a summary of the major findings from the research efforts; other reports contain additional details on the efforts undertaken during this research project.(4,5)

SPEED-PROFILE MODEL

In this research project, several different efforts were undertaken to predict operating speed for different conditions such as on horizontal curves, vertical curves, and on a combination of horizontal and vertical curves; on tangent sections; and prior to or after a horizontal curve. Speed data were collected at over 200 two-lane rural highway sites for use in the project. In addition to using the data to develop speed prediction equations for horizontal and vertical alignments, the effects of spiral curves and vehicle types were examined. Regression equations were developed for passenger car speeds for most combinations of horizontal and vertical alignment. Table 1 lists the developed equations and/or the assumptions made for the different alignment conditions.

Table 1. Speed Prediction Equations for Passenger Vehicles.

AC EQ# (see note 1)	Alignment Condition	Equation (see note 2)	Num. Sites	R^2	MSE
1.	Horizontal Curve on Grade : -9% # G < -4%	$V_{85}\ '\ 102.10\ \&\ \frac{3077.13}{R}$	21	0.58	51.95
2.	Horizontal Curve on Grade : -4% # G < 0%	$V_{85}\ '\ 105.98\ \&\ \frac{3709.90}{R}$	25	0.76	28.46
3.	Horizontal Curve on Grade : 0% # G < 4%	$V_{85}\ '\ 104.82\ \&\ \frac{3574.51}{R}$	25	0.76	24.34
4.	Horizontal Curve on Grade : 4% # G < 9%	$V_{85}\ '\ 96.61\ \&\ \frac{2752.19}{R}$	23	0.53	52.54
5.	Horizontal Curve Combined with Sag Vertical Curve	$V_{85}\ '\ 105.32\ \&\ \frac{3438.19}{R}$	25	0.92	10.47
6.	Horizontal Curve Combined with Non-Limited Sight Distance Crest Vertical Curve	(see note 3)	13	n/a	n/a
7.	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (i.e., K # 43 m/%)	$V_{85}\ '\ 103.24\ \&\ \frac{3576.51}{R}$ (see note 4)	22	0.74	20.06
8.	Sag Vertical Curve on Horizontal Tangent	V_{85} = *assumed desired speed*	7	n/a	n/a
9.	Vertical Crest Curve with Non Limited Sight Distance (i.e., K > 43 m/%) on Horizontal Tangent	V_{85} = *assumed desired speed*	6	n/a	n/a
10.	Vertical Crest Curve with Limited Sight Distance (i.e., K # 43 m/%) on Horizontal Tangent	$V_{85}\ '\ 105.08\ \&\ \frac{149.69}{K}$	9	0.60	31.10

NOTES:

1. AC EQ# = Alignment Condition Equation Number
1. Where: V_{85} = 85th percentile speed of passenger cars (km/h)
   K = rate of vertical curvature
   R = radius of curvature (m)
   G = grade (%)
3. Use lowest speed of the speeds predicted from equations 1 or 2 (for the downgrade) and equations 3 or 4 (for the upgrade).
4. In addition, check the speeds predicted from equations 1 or 2 (for the downgrade) and equations 3 or 4 (for the upgrade) and use the lowest speed. This will ensure that the speed predicted along the combined curve will not be better than if just the horizontal curve was present (i.e., that the inclusion of a limited sight distance crest vertical curve result in a higher speed).

For passenger vehicles, the best form of the independent variable in the regression equations is 1/R (i.e., inverse radius). Operating speeds on horizontal curves are very similar to speeds on long tangents when the radius is approximately 800 m or more. When this condition occurs, the grade of the section controls and the contribution of the horizontal radius is negligible. Operating speeds on horizontal curves drop sharply when the radius is less than 250 m. Figure 1 illustrates the collected data and the developed regression equations.

Passenger vehicle speeds on limited sight distance (LSD) vertical curves on horizontal tangents could be predicted using one over the rate of vertical curvature(1/K) as the independent variable. A statistically significant regression equation was not found for crest curves where the sight distance is not limited; therefore, the desired speed was assumed. For sag curves on horizontal tangents, the plot of the seven available data points and the regression analysis indicate that the desired speed should be assumed. Figure 2 illustrates the data and the suggested regression equation for limited sight distance crest curves.

For non-limited sight distance (NLSD) crest vertical curves in combination with horizontal curves, the lower speed of 1) the speeds predicted using the equations developed for horizontal curves on grades or 2) the assumed desired speed should be used. The collected speed data for that condition were generally for large horizontal curve radii with several of the speeds being above 100 km/h. Drivers may not have felt the need to reduce their speed in response to the geometry for these large radius horizontal curves. For the horizontal curvature combined with either sag or limited sight distance crest vertical curves, the radius of the horizontal curve was the best predictor of speed. Figure 3 shows the data and regression equations for combination curves.

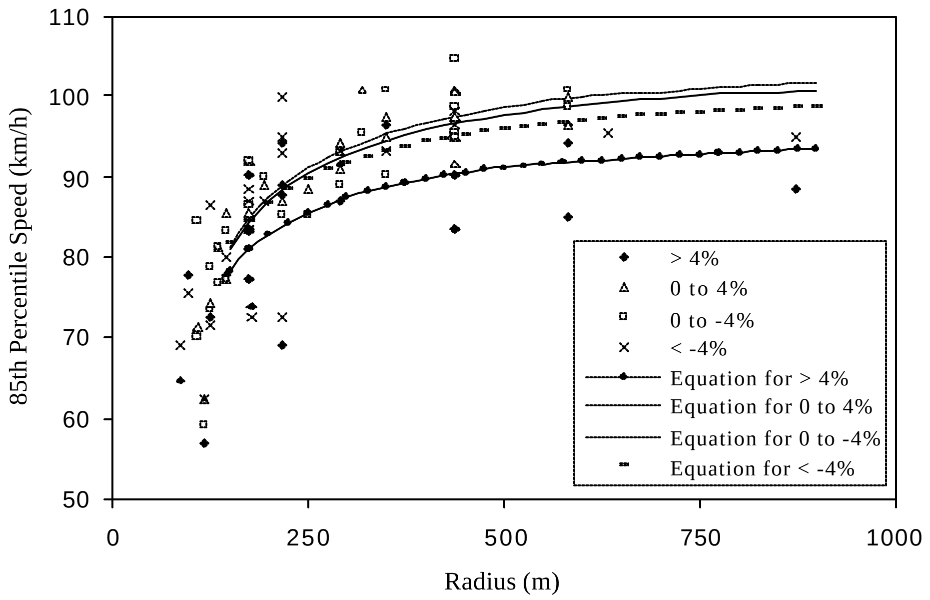

Figure 1. Horizontal Curves on Grades: V_{85} versus R.

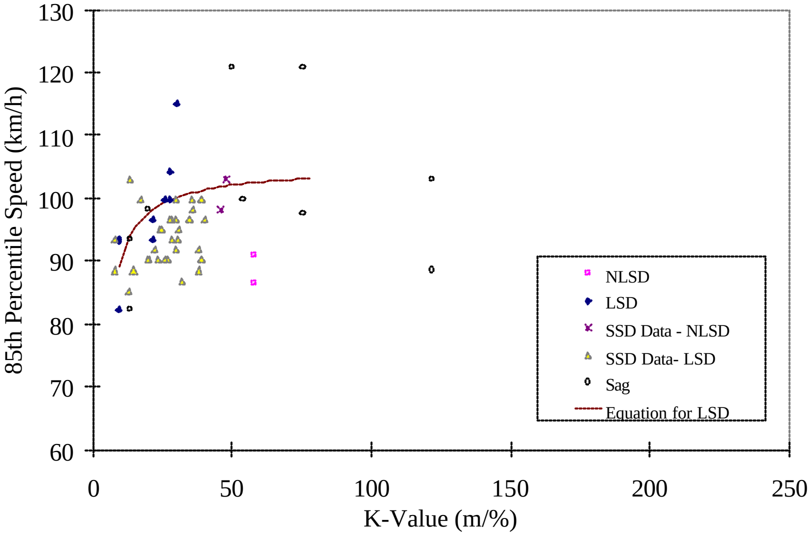

Figure 2. Vertical Curves on Horizontal Tangents: V_{85} versus K.

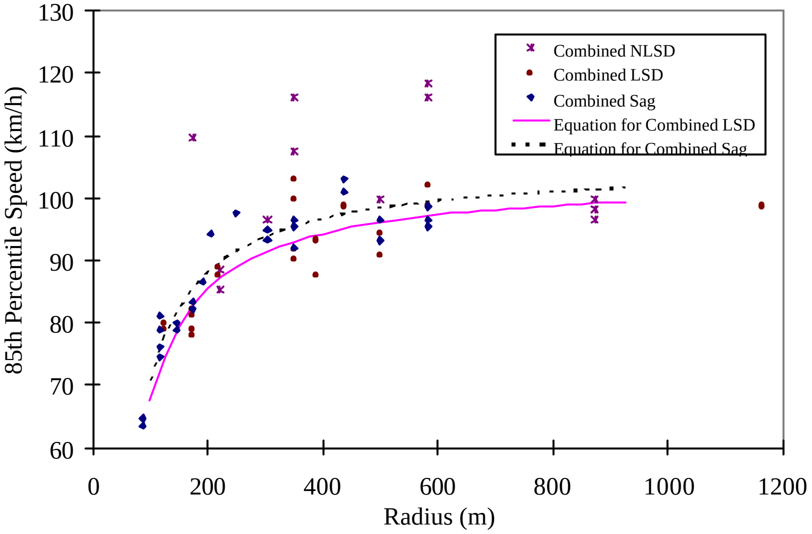

Figure 3. Combination Curves: V_{85} versus R.

The analysis of spiral curves found that the use of spirals did not result in a significant difference in speed when compared to similar sites without spirals. Because most of the study sites had few spot-speed observations for trucks and recreational vehicles, a limited analysis was performed for those sites with a minimum of 10 observations. The limited graphical analysis on trucks and recreational vehicles (RVs) showed that the truck/RV speeds plotted near the passenger car regression line with more of the data being below than above the line. Similar to the passenger car data, the truck/RV data showed lower speeds for smaller radii curves. Therefore, a design consistency evaluation should use the equations based on passenger car data.

Data were collected and analyzed at 21 sites to determine appropriate acceleration and deceleration values prior to and after a horizontal curve. The validation results indicate that the acceleration and deceleration assumptions employed in the previous speed-profile model are not valid for the set of study sites selected in this study.(3) The only sites with acceleration and deceleration rates which approached 0.85 m/s^2 were those with curve radii less than 250 m. New models were developed to consider the effects of curve radius on acceleration/deceleration rates. The models were based on maximum acceleration and deceleration rates observed at the study sites. Table 2 lists the developed acceleration/deceleration equations and values.

The speed data collected in the field were used to determine whether alignment indices can accurately predict speeds on a tangent. Additionally, other possible influences of desired speeds of motorists were examined. The findings of this research indicated that combinations of alignment indices and other geometric variables were not able to significantly predict the 85th percentile speeds of motorists on long tangents of two-lane rural highways. Other geometric variables examined included region, total pavement width, vertical grade, driveway density, and roadside rating.

For those situations when a vehicle is traveling on an upgrade or downgrade, the equations used in the TWOPAS model can be used to estimate speed for different vehicle types.(6) The model can be used to predict the speed of the vehicle at any point on the grade if its initial speed at the entry to the grade is known.

A speed-profile model was developed from the previously discussed findings. The model can be used to evaluate the design consistency of a facility or to generate a speed profile along an alignment. The steps to follow in the model are shown in figure 4. The initial step is to select the desired speed along the roadway. Based upon the findings from the research, the average 85th percentile speeds on long tangents range between 93 and 104 km/h for the different states in this study. Therefore, a speed of 100 km/h is a good estimate of the desired speed along a two-lane rural roadway when seeking a representative, rounded speed.

The speed prediction equations are listed in table 1. The speeds predicted using these equations represent the speeds measured at the midpoint of the curve. The model assumes, however, that this speed is constant throughout the horizontal or vertical curve. The equations used in the TWOPAS model can be used to check the performance-limited speed at every point on the roadway (upgrade, downgrade, or level). If at any point the grade-limited speed is less than the tangent or curve speed predicted using the speed prediction equations or the assumed desired speed, then the grade-limited speed will govern.

The speeds predicted from the previous three methods (assumed desired speed, speeds predicted using the speed prediction equations, and the speeds from the TWOPAS equations) are compared and the lowest speed selected. If a continuous speed profile for the alignment is needed, these speeds would then be adjusted for deceleration and acceleration using the speed- profile rates listed in table 2. Figure 5 illustrates the different conditions that can occur with supporting equations listed in table 3. The speeds for the different alignment features could be compared at any step in the speed-profile model to identify unacceptable changes in speed between alignment features. For example, a flag could be raised if the speed change from one curve to another is greater than (or equal to) a preset value such as:

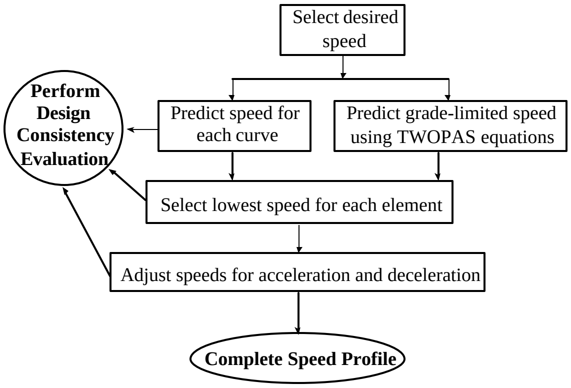

Figure 4. Speed-Profile Model Flowchart.

Good design ªV85 # 10 km/h
Fair design 20 km/h $ªV85 $10 km/h
Poor design ªV85 $20 km/h

In addition, a flag could be raised if acceleration or deceleration is greater than desired using the values listed in the table 2.

VALIDATION OF SPEED PREDICTION EQUATIONS

An initial effort within this study was to develop speed prediction equations using only part of the collected data (91 total sites). Six equations were developed from the data. Between 5 and 28 sites were used in each equation development. The speeds predicted from these equations were then compared to the observed values at similar sites. Between 3 and 22 sites were used in the comparisons for a total of 68 sites. Figure 6 shows the plot of the speed that was predicted using the equation to the speed observed in the field for each of the 68 sites. The 6 speed prediction equations performed well in the validation effort with a range of mean absolute percent error between 4.1 and 10 percent. Therefore, all of the data available as part of this research study was then used to developed the speed prediction equations listed in table 1.

SPEED DISTRIBUTION MEASURES

Measures of vehicle operations that may be an appropriate basis for consistency rating methods include speed variance, lateral placement (mean and variance), erratic maneuvers, and traffic conflicts. These measures have been evaluated as surrogate measures of accident experience and measures of effectiveness of delineation treatments.(7-10) In roadway delineation research, speed variance and lateral placement variance have been considered as indicators of the effectiveness of alternative treatments at reducing errors in the guidance level of the driving task. Design inconsistencies also increase guidance-level errors, and it is reasonable to hypothesize that these measures would be correlated with and could complement speed reduction in evaluating design consistency.

Table 2. Deceleration and Acceleration Rates.

Deceleration Rate, d (m/s^2)		**Alignment Condition**		**Acceleration Rate, a (m/s^2)**	
Speed Profile					
Radius, R (m)	d	1-4	Horizontal Curves on Grade: -9% # G < 9%	Radius, R (m)	a
R $ 436	0.00			R > 875	0.00
175 # R < 436	% 0.6794 & $\frac{295.14}{R}$			436 < R # 875	0.21
				250 < R # 436	0.43
R < 175	1.00			175 < R # 250	0.54
1.00		5	Horizontal Curve Combined with Sag Vertical Curve	0.54	
(use rates for Alignment Conditions 1 to 4)		6	Horizontal Curve Combined with Non-Limited Sight Distance Vertical Curve	(use rates for Alignment Conditions 1 to 4)	
1.00		7	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (i.e., K # 43 m/%)	0.54	
n/a		8	Sag Vertical Curve on Horizontal Tangent	n/a	
n/a		9	Vertical Crest Curve with Non- Limited Sight Distance (i.e., K > 43 m/%) on Horizontal Tangent	n/a	
1.00		10	Vertical Crest Curve with Limited Sight Distance (i.e., K # 43 m/%) on Horizontal Tangent	0.54	
where: K = rate of vertical curvature G = grade (%)					
Design Consistency (all alignment conditions)					
1.00 to 1.48		Good Design		0.54 to 0.89	
1.48 to 2.00		Fair Design		0.89 to 1.25	
>2.00		Poor Design		> 1.25	

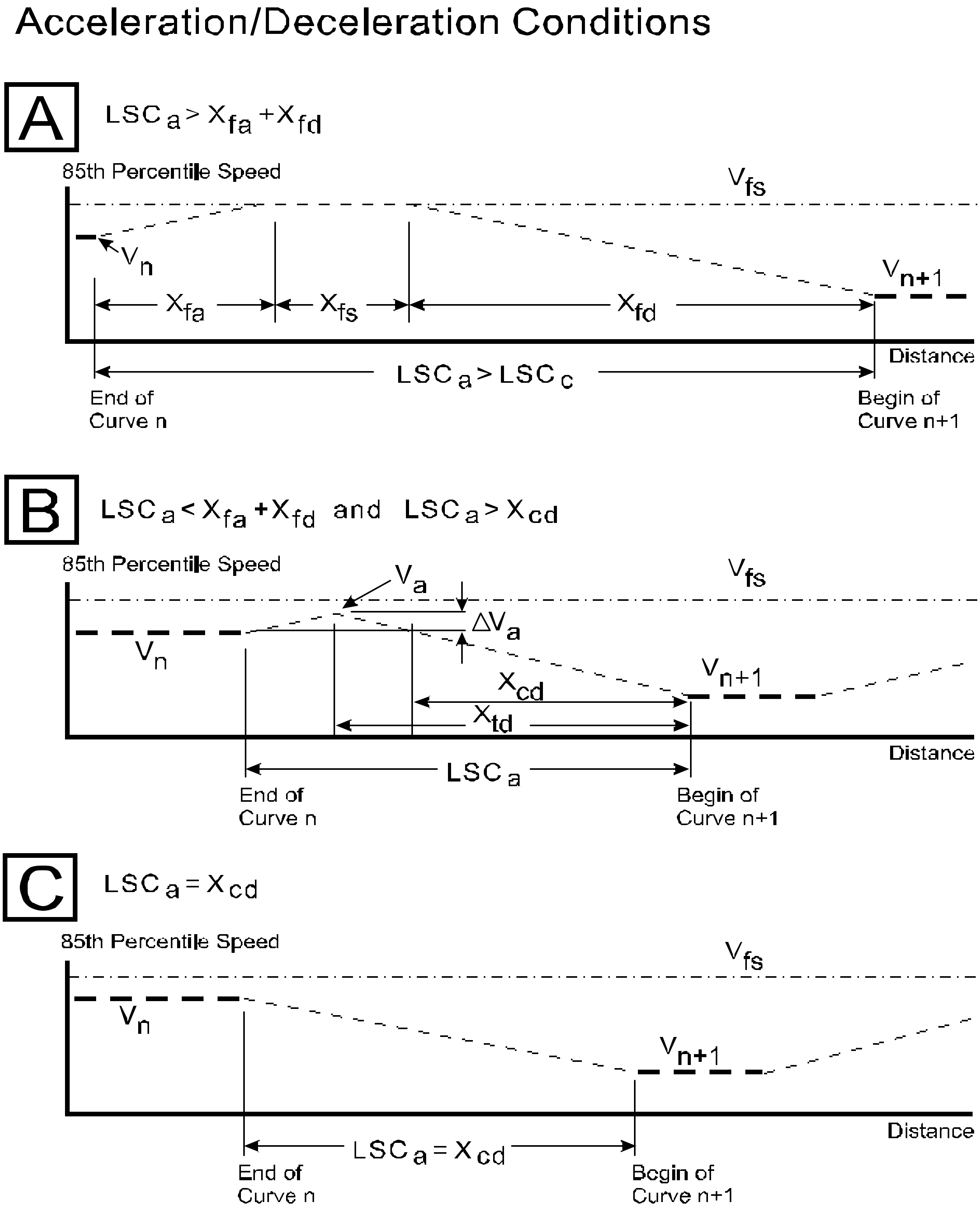

Figure 5. Acceleration/Deceleration Conditions.
(See table 3 for variable definitions.)

Acceleration/Deceleration Conditions

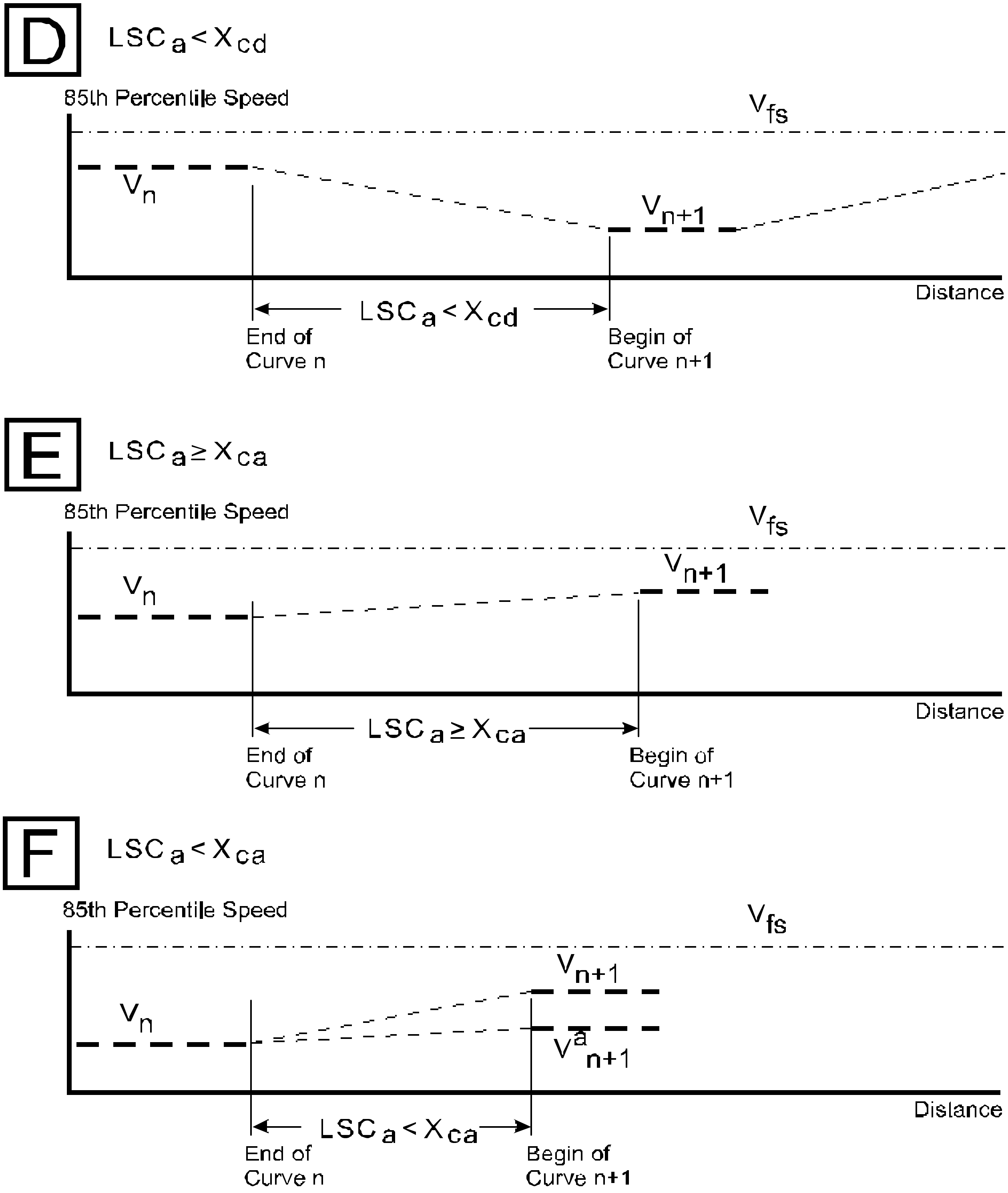

Figure 5. Acceleration/Deceleration Conditions (continued).

Table 3. Equations for Use in Determining Acceleration and Deceleration Distances.

$$LSC_c = \frac{2V_{fs}^2 - V_n^2 - V_{n+1}^2}{25.92\ d} \qquad (1)$$

$$X_{fd} = \frac{V_{fs}^2 - V_{n+1}^2}{25.92\ d} \qquad (2)$$

$$X_{cd} = \frac{V_n^2 - V_{n+1}^2}{25.92\ d} \qquad (3)$$

$$X_{ca} = \frac{V_{n+1}^2 - V_n^2}{25.92\ a} \qquad (4)$$

$$X_{fa} = \frac{V_{fs}^2 - V_n^2}{25.92\ a} \qquad (5)$$

$$X_{fs} = LSC_a - X_{fd} - X_{fa} \qquad (6)$$

$$X_{td} = \frac{V_a^2 - V_{n+1}^2}{25.92\ d} \qquad (7)$$

$$V_a = V_n + \Delta V_a \qquad (8)$$

Note: when calculating V_a the curve with the larger radius is to be used.

$$\Delta V_a = \frac{-2V_n + [4V_n^2 + 44.06(LSC_a - X_{cd})]^{\overline{\frac{1}{2}}}}{2} \qquad (9)$$

$$V_{n+1}^a = V_n + a\ (LSC_a) \qquad (10)$$

Where:

V_{fs} = 85th percentile desired speed on long tangents (m)
V_n = 85th percentile speed on Curve n (km/h)
V_{n+1} = 85th percentile speed on Curve n + 1 (km/h)
V^a_{n+1} = 85th percentile speed on Curve n + 1 determined as a function of the assumed acceleration rate (km/h)
V_a = maximum achieved speed on roadway between curves in conditions B (km/h)
$?V_a$ = difference between speed on Curve n and the maximum achieved speed on roadway between curves in Condition B (km/h)
d = deceleration rate, see table 2 (m/s^2)
a = acceleration rate, see table 2 (m/s^2)
LSC_c = critical length of roadway to accommodate full acceleration and deceleration (m)
LSC_a = length of roadway available for speed changes (m)
X_{fd} = length of roadway for deceleration from desired speed to Curve n + 1 speed (m)
X_{cd} = length of roadway for deceleration from Curve n speed to Curve n + 1 speed (m)
X_{td} = length of roadway for deceleration from V_a to Curve n + 1 speed (m)
X_{ca} = length of roadway for acceleration from Curve n speed to Curve n + 1 speed (m)
X_{fa} = length of roadway for acceleration from Curve n speed to desired speed (m)
X_{fs} = length of roadway between two speed limited curves at desired speed (m)

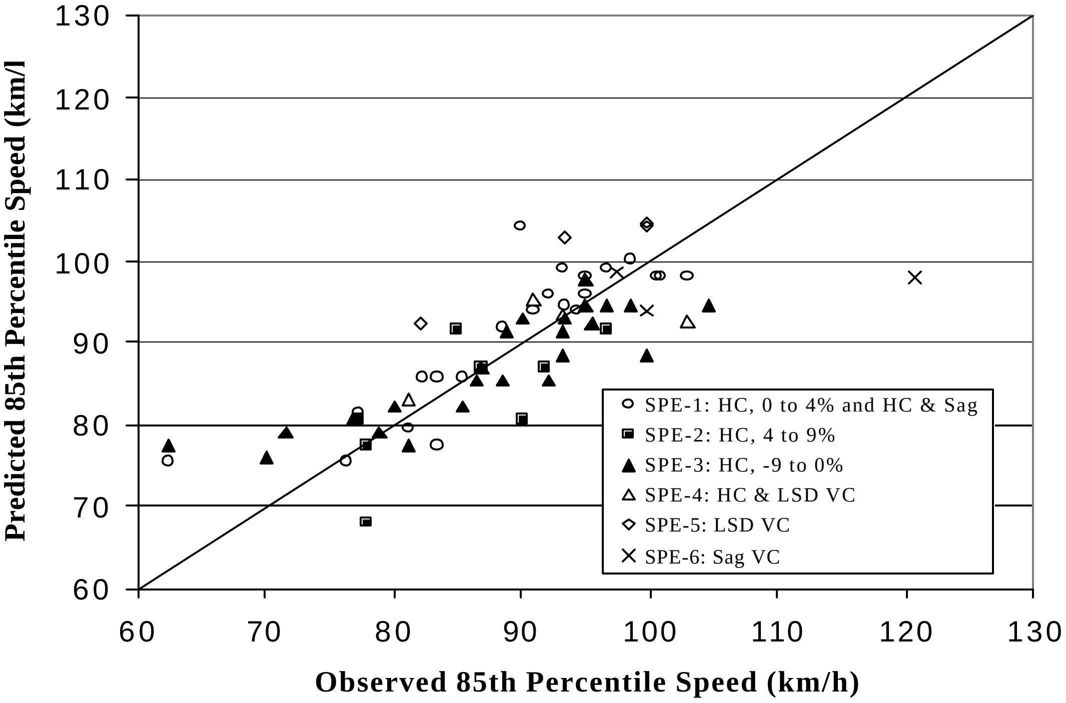

Figure 6. Predicted versus Observed V_{85} at Midpoint of Curve.

Speed distribution measures—including variance, standard deviation, coefficient of variation, and coefficient of skewness—are logical candidates for a consistency rating method to complement speed reduction estimates from the 85th percentile speed models. The rationale for using spot-speed variability measures is that inconsistent features are expected to cause more driver errors and greater variation in guidance-level decisions (i.e., speed and path choice) than consistent features. Correspondingly, it was hypothesized that inconsistent features would exhibit more spot-speed variability than consistent features and that single-vehicle accidents resulting from guidance-level errors will increase with increasing speed variability.

Graphical evaluations were initially performed to obtain an appreciation of how the speed distribution measures varied in relationship to roadway geometry and speed measures, such as posted speed. For horizontal curves, standard deviation of speed generally varied from 6 to 12 km/h as illustrated in figure 7. As mean speed increased, standard deviation of speed became more variable, suggesting that restrictive geometry controlled both mean speed and standard deviation for small radius horizontal curves. The graphical analysis of the effects of roadway geometry on speed distribution measures presented no clear indication of a relationship between any of the measures (variance, standard deviation, coefficient of variation, coefficient of skewness, coefficient of kurtosis) and geometric elements (tangent length, horizontal curve radius, horizontal or vertical curve length, deflection angle, superelevation, lane/pavement width, rate of vertical curvature, approach grade, departure grade) with one exception. For radii 100 m and less, standard deviation was lower than for larger radii.

The analyses conducted to examine the relationship between standard deviation of speeds and design or posted speed also did not produce any significant relationships. Expected trends in the data were found which related speed measures to these two speed components, but the variation of the data suggested that design and posted speed were not accurate predictors of speed distribution measures. In addition, an evaluation using regression was also performed. Linear relationships between speed distribution measures of successive features existed because the same sample of drivers were being measured. Extreme differences existed for some locations where the horizontal distribution measures did not fit the linear trend with respect to the tangent measures. These locations may be locations where inconsistencies are present, but without accident data no inferences can be made regarding these design inconsistencies.

In summary, the results from the analyses indicated that speed variance generally decreased on horizontal curves as compared to the upstream tangent. Given this finding and the limited statistical relationships, it is not appropriate to consider speed variance as a design consistency measure for horizontal curvature.

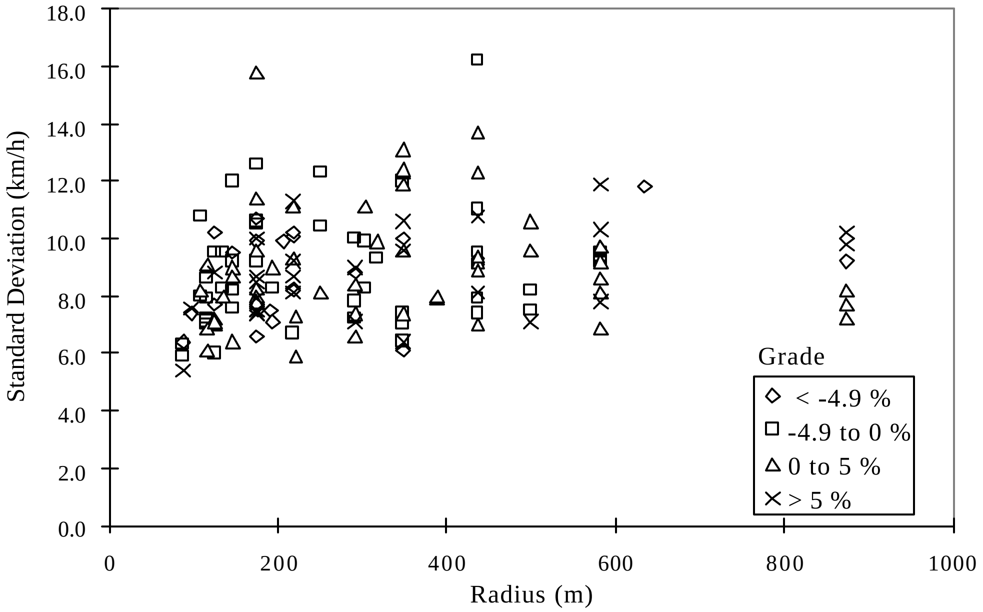

Figure 7. Horizontal Curve Speed Standard Deviation versus Radius.

Alignment INDICES

In this study, one of the alternative methods investigated for rating the design consistency of a roadway was alignment indices. Alignment indices are quantitative measures of the general character of a roadway segment's alignment. Problems with geometric inconsistencies arise when the general character of alignment changes between segments of roadway. A common example is where the terrain transitions from level to rolling or mountainous, and the alignment correspondingly changes from gentle to more severe. Proposed indicators of geometric inconsistency are large increases in the magnitude of alignment indices for successive roadway segments or a high rate of change in alignment indices over some length of roadway.

Germany uses a horizontal alignment index that indicates the alignment severity.(11) The British use two indices–one for alignment and one for layout–to check for compatibility between a roadway segment's design speed and likely operating speeds on the roadway.(12) Polus and Dagan proposed alignment indices based upon: the proportion of a roadway section that is curved, the ratio of the minimum and maximum radii of a roadway section, the ratio of the average radius of curves on a roadway section to the minimum radius for the roadway's design speed, and a spectral analysis of the extent to which the alignment exhibits a cyclical or repeating pattern.(13) Their preliminary evaluations suggested that such indices hold promise as measures of consistency.

Table 4 provides a list of the alignment indices selected for use in this study. This table also shows the equations necessary to compute the indices and the resulting units. These indices were initially used to determine if they, together with other geometric variables such as vertical grade, could predict speed on a tangent. A subset of the alignment indices shown in table 4 that were selected for examination as possible measures in rating the design consistency of two-lane rural highways included: Average Radius, Maximum Radius/Minimum Radius, Average Tangent Length, and Average Rate of Vertical Curvature. In addition, the ratio of individual curve radius to average radius and the ratio of individual tangent length to average tangent length were also examined.

None of the alignment indices studied were statistically significant predictors of the desired speeds of motorists on long tangents of two-lane rural highways. Of the geometric variables examined, only the vertical grade at the tangent site significantly affected the desired speeds of motorists on long tangents of two-lane rural highways. The relationship of alignment indices to safety is discussed below in the section titled Relationship of Design Consistency Measures to Safety.

DRIVER WORKLOAD

Generally, little visual information processing capacity is required of the experienced driver to perform the driving task on two-lane rural highways. A consistent roadway geometry allows a driver to accurately predict the correct path while using little visual information processing capacity, thus allowing attention or capacity to be dedicated to obstacle avoidance and navigation. Several research efforts have been undertaken to measure the effects of design consistency on driver workload. The logic underlying these efforts is that the more difficult or unusual a feature or feature combination, the greater the visual information processing requirement and, in turn, the less desirable the feature.

This current project validated and extended work begun previously by Krammes et al.(3) Like the previous study, a test-track study to examine driver workload was performed. Companion efforts using on-road studies, simulator studies, and an eye-mark system were also performed. Curve sequence, radius, deflection angle, and separation distance between curves were examined through the use of vision occlusion and subjective ratings.

Table 4. Alignment Indices Selected for Evaluation.

Horizontal Alignment Indices

- Curvature Change Rate - CCR (deg/km)

$$\frac{\sum \Delta_i}{\sum L_i}$$

where:
Δ = deflection angle (deg)
L = length of section (km)

- Degree of Curvature - DC (deg/km)

$$\frac{\sum DC_i}{\sum L_i}$$

where:
DC = degree of curvature (deg)
L = length of section (km)

- Curve Length: Roadway Length - CL:RL

$$\frac{\sum (CL)_i}{\sum L_i}$$

where:
CL = curve length (m)
L = length of section (m)

- Average Radius - AVG R (m)

$$\frac{\sum R_i}{n}$$

where:
R = radius of curve (m)
n = number of curves within section

- Average Tangent - AVG T (m)

$$\frac{\sum (TL)_i}{n}$$

where:
TL = tangent length (m)
n = number of tangents within section

Vertical Alignment Indices

- Vertical CCR - V CCR (deg/km)

$$\frac{\sum A_i}{\sum L_i}$$

where:
A = absolute difference in grades (deg)
L = length of section (km)

- Average Rate of Vertical Curvature - V AVG K (km/%)

$$\frac{\sum \frac{L}{|A|}}{n}$$

where:
L = length of section (km)
A = algebraic difference in grades (%)
n = number of vertical curves

- Average Gradient - V AVG G (m/km)

$$\frac{\sum |\Delta E_i|}{\sum L_i}$$

where:
ΔE = change in elevation between VPI_{i-1} and VPI (m)
L = length of section (km)

Composite Alignment Indices

- Combination CCR - COMBO (deg/km)

$$\frac{\sum \Delta_i}{\sum L_i} + \frac{\sum A_i}{\sum L_i}$$

where:
Δ = deflection angle (deg)
A = absolute difference in grades (deg)
L = length of section (km)

In the vision occlusion procedure, drivers wore a Liquid Crystal Display (LCD) visor that was opaque except when the driver request a 0.5 s glimpse through the use of a floor-mounted switch. The visual demand was computed as the ratio of the glimpse length divided by the time elapsed from the last glimpse until the time of the present request. The calculation provides a measure of the percentage of time that a driver is observing the roadway at any point along the roadway. The value increases as the time between successive glances grows shorter, and decreases as the interval between glances increases. The more information the driver needs for controlling of the driving function, the more often the scene ahead must be sampled, i.e., the workload increases.

In a second phase to the vision occlusion testing, the glimpses were received at a rate set by the experimenter. Beginning at a point that did not provide sufficient vision to drive the roadway, the rates were progressively increased until the drivers could successfully drive the features. An assessment of the tolerance for workload change were developed by comparing the visual demand during the driver-controlled vision occlusion to the visual demand during the experimenter-controlled vision occlusion.

Subjective ratings were obtained using a modified Cooper-Harper scale, used widely in aircraft testing. The scale ranges from 1 (very easy) to 10 (impossible). Descriptive terms were modified to relate the scale to the driving environment, and anchor definitions were provided to ensure that drivers compared the scaling to familiar circumstances.

Visual demand was determined at three types of facilities: test track environment (24 subjects driving 6 single curves and 4 paired curves for 6 runs), on-road (6 subjects driving 5 curves for 4 runs), and simulation (24 subjects driving 12 curves for 6 runs). The general pattern was for the visual demand to begin to rise about 90 m from the beginning of the curve, peak near the beginning, remain level or slightly drop through the curve, and then gradually return to the baseline level after the end of the curve. Figure 8 illustrates this pattern for the test track data.

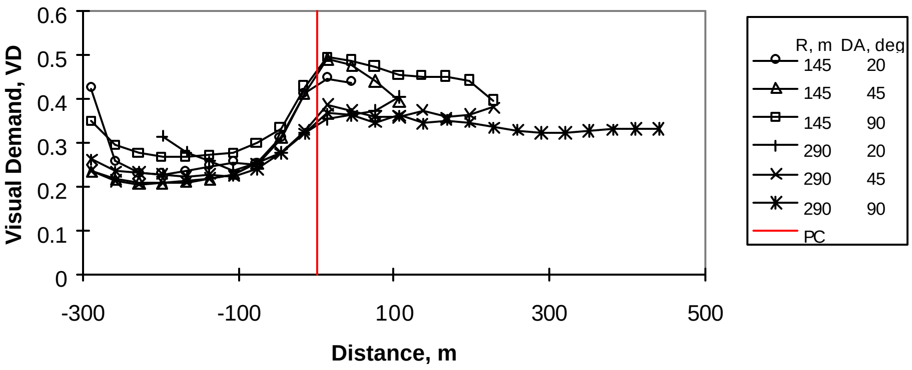

Figure 8. Visual Demand Averaged Over All Subjects for Each Single Curve.

To compare the data between testing facilities, two measures were calculated: VD and VD_{30}. VD is the visual demand averaged over the length of the curve. Because this approach results in a value that is directly proportional to the length of the curve and long curves may have lower VD values because more of the lower "tail" is included in the calculation, other measures were investigated. The visual demand for the initial 30 m following the PC (VD_{30}) was also calculated and compared between testing facilities. This measure allows for a better understanding of the effect of the roadway geometry in or near the peak VD, although the absolute peak associated with a particular run might or might not be included in that 30 m.

Driver workload increases linearly with the inverse of radius. That is, as radius becomes smaller, driver workload increases. This finding is supported by the variety of measures and techniques used to evaluate driver workload. Both subjective (modified Cooper-Harper rating) and objective (visual demand) measures of driver workload indicated similar trends. The effect of deflection angle was persistent but small in overall influence and practical significance for driver workload. Analyses examining subjective and objective measures indicated a modest effect, although the subjective measure (modified Cooper-Harper rating) provided a clearer indication of the influence of deflection angle on workload.

The examination of paired curves revealed that neither type of curve pair (i.e., broken back- or S-curve) nor curve pair separation greatly influenced VD, although their influence was statistically significant. Somewhat contradictory results were found, indicating different responses depending on the run. An interaction between separation and pair type indicated that closely spaced S-curves had significantly higher workload than closely spaced broken-back curves when run 1 results were examined. Runs 2-6 results indicated that widely spaced curves had higher VD than closely spaced curves. Both of these findings were unexpected. It was anticipated that S-curves would be more consistent with driver expectations (and be associated with lower workload) and that more closely spaced curves would impose a greater workload through carryover from the previous curve. The VD changes observed were relatively small, however, and further research should be conducted to confirm or extend these results.

When vision was not occluded in simulation occlusion test sessions, drivers primarily looked ahead searching for points where roads curved and generally ignored edge markings in the near field. Where in the distance drivers looked depended upon the curve direction (left or right) and how sharp the curve was. The sharper the curve, the more likely drivers were to look at the outside lane line (versus the inside lane line). This finding may have implications for delineation placement (i.e., providing enhanced outside lane line treatments for sharp curves).

Several different workload measures and testing environments were used in the course of this research project. Figure 9 provides overall visual comparisons for VD. Examining the figure, it is apparent that the measures used in the project to represent driver workload were relatively robust. Of the six possible comparisons, statistical analyses showed that five resulted in the conclusion that no significant difference in slope (with respect to the inverse of radius) existed between the TTI test track study regression equations and the comparison equations. This finding provides a level of confidence that workload differences between features can reliably be predicted. The exception to this finding was between the current test track study and the simulator study for one measure of workload, VD.

The comparisons between intercepts, or constants, yielded the finding that those intercepts were generally significantly different. The cause for these differences is difficult to determine exactly, but differences in roadway markings (i.e., alternating markers every 9.2 m compared to markers on both sides every 6.1 m, painted center stripes and edge lines compared to raised markings, etc.), testing environments (test track versus simulator, test track versus highway), and the use of different subjects probably account for many of the differences.

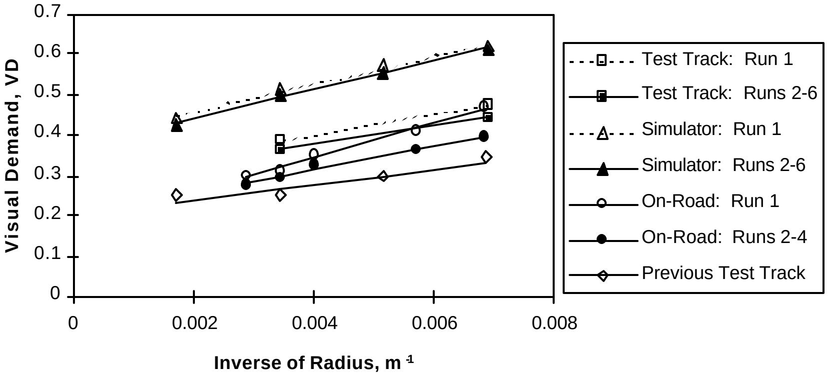

Figure 9. Overall Equations: VD.

The finding that there is no difference in the slope of the regression line when comparing test track results with on-road results, but that there is a difference in the intercept, would indicate that *relative* levels of workload can be ascertained, but not *absolute* levels. This finding shows promise in determining *differences* in workload levels between successive highway features, but not in baseline levels. Because most applications of driver workload are expected to be with respect to changes in level rather than in absolute terms, the general agreement with respect to the slope of the workload measures used is very encouraging. The overall robustness in response should yield a greater confidence in the measures used and lead to further use, research, and future application.

RELATIONSHIPS OF DESIGN CONSISTENCY MEASURES TO SAFETY

Before a design consistency methodology is recommended to geometric designers, however, it would be valuable to demonstrate that the proposed design consistency measures are, in fact, related to safety. Following is a summary of the evaluation. A database was developed to test the relationship to safety of the roadway alignment indices. To assemble this database, data were obtained from the FHWA Highway Safety Information System (HSIS) for state-maintained two-lane rural highways in the State of Washington. Criteria used in establishing study segments included: a minimum section length of 6.4 km, a maximum section length of 32 km, minimum posted speed limit of 88.5 km/h or more, and elimination of portions of roadway with features that might interfere with the analysis. These criteria resulted in 291 highway sections available for analysis. The analysis considered only non-intersection accidents between 1993 and 1995 that involved: 1) a single vehicle running off the road; 2) a multiple-vehicle collision between vehicles traveling in opposite directions; or 3) a multiple-vehicle collision between vehicles traveling in the same direction. All accidents involving parking, turning, or passing maneuvers, animals in the roadway, bicycles, or motorcycles were excluded.

The safety evaluation considered seven candidate design consistency measures: the speed reduction from one geometric design feature to another and six alignment indices. Regression models were developed to investigate the relationship between each candidate design consistency measure and safety. The statistical models developed were not intended for use as accident predictive models but were instead intended to illustrate the nature of the relationship of candidate design consistency measures to safety. Accident frequencies were modeled as a function of exposure (annual average daily traffic -- AADT -- and section length, both on the logarithmic scale) and each of the alignment indices taken one at a time. Sensitivity analyses were also conducted to examine the sensitivity of the predicted accident experience to the alignment index.

Of the candidate design consistency measures, four have relationships to accident frequency that are statistically significant and appear to be sensitive enough that they may be potentially useful in a design consistency methodology. These four candidate design consistency measures are:

- Predicted speed reduction by motorists on a horizontal curve relative to the preceding curve or tangent.
- Ratio of an individual curve radius to the average radius for the roadway section as a whole.
- Average rate of vertical curvature for a roadway section.
- Average radius of curvature for a roadway section.

Thus, these measures appear promising for assessing the design consistency of roadway alignments.

Of these candidate design consistency measures, the speed reduction on a horizontal curve relative to the preceding curve or tangent clearly has the strongest and most sensitive relationship to accident frequency. Table 5 is an example of the relationship between speed reduction between successive geometric elements and accident rates. Accident frequency is not as sensitive to the alignment indices reviewed as it is to the speed reduction for individual horizontal curves. In addition, the evaluation has shown that the speed reduction to a horizontal curve is a better predictor of accident frequency than the radius of that curve. This observation makes a strong case that a design consistency methodology based on speed reduction provides a better method for anticipating and improving the potential safety performance of a proposed alignment alternative than a review of horizontal curve radii alone.

Table 5. Accident Rates at Horizontal Curves by Design Safety Level.

Design safety level*	Number of horizontal curves	3-yr accident frequency	Exposure (million veh-km)	Accident rate (accidents/ million veh-km)
Good: ªV85 # 10 km/h	4,518	1,483	3,206.06	0.46
Fair: 10 km/h < ªV85 # 20 km/h	622	217	150.46	1.44
Poor: ªV85 > 20 km/h	147	47	17.05	2.76
Combined	5,287	1,747	3,373.57	0.52
*ªV85 = difference in 85th percentile speed between successive geometric elements (km/h)				

CONCLUSIONS

The following general conclusions were developed based upon the findings of the study.

Speed-Profile Model

- This research produced speed prediction equations that can be used to calculate the expected 85th percentile speed along an alignment that includes both horizontal and vertical curvature.

- The average 85th percentile speed for long tangents ranged from 93 to 104 km/h for the states in this study. Based on the data and engineering judgment, the operating speeds on tangents and the maximum operating speeds on horizontal curves could be rounded to 100 km/h.

- After establishing that current acceleration and deceleration rates and assumptions are not valid, at least for the sites selected in this study, new models were developed that predict acceleration and deceleration in the vicinity of a horizontal curve as a function of curve radius.

- The various findings from this study were used to develop a speed-profile model. This model can be used to evaluate the design consistency of a facility or to generate a speed profile along an alignment.

- The speed-profile model developed in the research appears to provide a suitable basis for the IHSDM design consistency module. Therefore, IHSDM should contain a design consistency module based on the speed-profile model developed in this research.

Alignment Indices

- The alignment indices did not explain the variation in measured speeds on long tangents nor are they as sensitive to accident frequency as speed reduction predictions.

Speed Distribution Measures

- Based upon the findings from this research, speed variance is not appropriate as a design consistency measure for horizontal curves.

Driver Workload

- Driver workload has very good potential as a design consistency rating measure. Additional investigation is necessary to develop threshold values indicating limits to driver workload change, with the work examining workload tolerance performed in this study providing a starting point.

- The vision occlusion method is sensitive to changes in road geometry and is a promising measure of effectiveness. Vision occlusion should be considered for use in future studies when the visual demand/workload of driving situations is to be determined.

- The preferred method of computing vision demand for a horizontal curve is over a relatively small fixed-length portion of roadway after the beginning of the curve to eliminate potential confounding between the summary measures used and the length of the curve. In this study measures based on the first 30 m of the test curves were used successfully.

- Based on this research, simulator results can provide reasonable estimates of real world estimates of workload and should be considered for use in future studies of visual demand.

Relationships of Design Consistency Measures to Safety

- Of the candidate design consistency measures, the speed reduction on a horizontal curve relative to the preceding curve or tangent has the strongest relationship to accident frequency.

- The following alignment indices are also related to safety:

- Ratio of an individual curve radius to the average radius for the roadway section as a whole.
- Average rate of vertical curvature for a roadway section.
- Average radius of horizontal curvature for a roadway section.

However, these alignment indices are not as strongly related to safety as speed reduction.

RECOMMENDATIONS

The following recommendations are made based upon the findings and conclusions of this study:

- Additional insight into the influence of speeds on tangent sections of various lengths and grades is needed. This proposed research would greatly enhance the effectiveness of any speed-profile model because it may validate the assumptions currently being made.

- The acceleration and deceleration models developed here were exclusively related to the impact of the horizontal curve. It is recommended that a similar effort be undertaken to assess the impact of vertical curves, as well as horizontal-vertical curve combinations on acceleration and deceleration profiles.

- Further research should be conducted to extend all aspects of this research, such as speed prediction equations, acceleration/deceleration behavior, and the speed-profile model, to roadway types other than two-lane rural highways.

- Further refinements should be made to the IHSDM design consistency module in future research to include a capability to identify design inconsistencies based on factors other than horizontal and vertical alignment. Such factors might include intersections, driveways, and auxiliary lanes.

- Further research should be conducted in estimating operating speeds of trucks and recreational vehicles for different horizontal and vertical curves. Additional data are required to develop regression models to estimate their operating speeds.

- Because the safety evaluation demonstrated that predicted speed reduction has the strongest relationship to accident frequency, speed reduction should be the primary measure in any design consistency methodology for horizontal and vertical curvature. To accomplish this, better methods to predict speeds need to be investigated. Alignment indices may be appropriate measures to supplement speed reduction in a design consistency methodology, but they should not be considered as the primary measure.

- Additional effort is recommended to apply the driver workload techniques evaluated and developed in this study to other design conditions (i.e., more complex curves, intersections, signs and signals, and traffic). Studies relating driver workload to traffic conflict or accident risk could assist in further evaluating its usefulness in geometric design. Low-cost simulation with on-the-road or test track inputs should be an essential element of that program.

- Additional research is desired to develop a better theoretical model of visual demand. Further studies of the influence of aging on visual demand would also enhance the possible application of driver workload measures.

REFERENCES

1. Reagan, J. "The Interactive Highway Safety Design Model: Designing for Safety by Analyzing Road Geometrics." *Public Roads*, Vol. 58, No. 1, 1994.
2. Lum, H., and J. Reagan. "Interactive Highway Safety Design Model: Accident Prediction Model." *Public Roads*, Vol. 58, No. 2, 1995.
3. Krammes, R., R.O. Brackett, M. Shafer, J. Ottesen, I. Anderson, K. Fink, K. Collins, O. Pendleton, and C. Messer. *Horizontal Alignment Design Consistency for Rural Two-Lane Highways*. FHWA-RD-94-034. Federal Highway Administration, Washington, D.C., 1995.
4. Fitzpatrick, K., L. Elefteriadou, D. W. Harwood, J. M. Collins, J. McFadden, I. B. Anderson, R. A. Krammes, N. Irizarry, K. D. Parma, K. Passetti, and K. M. Bauer. *Speed Prediction for Two-Lane Rural Highways*. Draft Final Report FHWA-RD-99-171. June 1999.
5. Fitzpatrick K., M. D. Wooldridge, O. Tsimhoni, J. M. Collins, P. Green, K. M. Bauer, K. D. Parma, R. Koppa, D. W. Harwood, I. B. Anderson, R. A. Krammes, and B. Poggioli. *Alternative Design Consistency Rating Methods for Two-Lane Rural Highways*. Draft Final Report FHWA-RD-99-172. January 1999.
6. St. John, A.D., and D. W. Harwood, *TWOPAS User's Guide*, Federal Highway Administration, Washington, D.C., May 1986.
7. Taylor , J., H. McGee, E. Seguin, and R. Hostetter. *Roadway Delineation Systems*. National Cooperative Highway Research Program Report, Highway Research Board, Washington, D.C., 1972.
8. Stimpson, W., H. McGee, W. Kittelson, and R. Ruddy. *Field Evaluation of Selected Delineation Treatments for Two-Lane Rural Highways*. FHWA-RD-77-118. Federal Highway Administration, Washington, D.C., 1978.
9. Datta, T., D. Perkins, J. Taylor, and H. Thompson. *Accident Surrogates for Use in Analyzing Highway Safety Hazards*. Volume 2. FHWA/RD-82/104. Federal Highway Administration, Washington, D.C., 1983.
10. Terhune, K. and M. Parker. *An Evaluation of Accident Surrogates for Safety Analysis of Rural Highways*. Volume 2. FHWA/RD-86/128. Federal Highway Administration, Washington, D.C., 1986.
11. Richtlinien für die Anlage von Straßen (RAS); Teil: Linienführung (RAS-L); Abschnitt 1: Element der Linienführung (RAS-L-1)[Guidelines for Street Design; Volume; Alignment; Section: Elements of Alignment]. Cologne, Germany: Forschungsgesellschaft für Strassen- und Verkerswesen Arbeitsgruppe Strassentwurf [Research Institute for Street and Traffic Studies, Street Design Work Group], 1984.
12. Highway Link Design. Departmental Advice Note TA 43/84. London, England: Department of Transport, 1984.
13. Polus, A. and D. Dagan. "Models for Evaluating the Consistency of Highway Alignment." *Transportation Research Record 1122*, 1987, pp. 47-56.