Highway Geometric Design Consistency Evaluation Software

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Previous research has concluded that horizontal curves on which design speeds are less than drivers' desired speeds exhibit operating speed inconsistencies that increase accident potential, and that current AASHTO design policy is unable to identify and address these inconsistencies. One step to address these concerns is the development by the FHWA of an Interactive Highway Safety Design Model that incorporates a consistency module. A Highway Geometric Design Consistency Program has been developed to serve as a basis for this consistency module. The program is a menu-driven microcomputer procedure for evaluating horizontal alignment consistency on rural two-lane highways using two preliminary models: an operating speed profile model and a driver workload profile model. This paper reviews these preliminary models, describes the menu-driven procedure for using them, and recommends future development of the models and procedure.

Previous research on rural two-lane highway operations and safety has concluded that horizontal curves on which design speeds are less than drivers' desired speeds exhibit operating speed inconsistencies that increase accident potential (*1–3*). Current AASHTO design policy is unable to identify and address operating speed inconsistencies (*4*). Therefore, it has been recommended that the design process for horizontal alignments on rural two-lane highways on which design speeds are less than 100 km/hr (62.1 mi/hr) be modified to incorporate a consistency evaluation that identifies and addresses operating speed inconsistencies (*1*). FHWA is taking steps toward implementing this recommendation by incorporating a consistency module in its Interactive Highway Safety Design Model (*5*).

This paper describes a program that has been developed to serve as the basis for the consistency module (*6*). The program is a menu-driven microcomputer procedure for evaluating horizontal alignment consistency on rural two-lane highways using two preliminary models: an operating speed profile model and a driver workload profile model. Both models have the same modest data requirements: the stationing of the point of curvature (PC) and the point of tangency (PT) of each horizontal curve along an alignment and each curve's radius or degree of curvature. Currently, the procedure requires the user to extract these data from roadway plans and enter it into an input data screen. In the ultimate implementation in the Interactive Highway Safety Design Model, the data required for the consistency module would be extracted automatically from the data base of the commercial computer-aided design (CAD) package that will be the hub of the model.

This paper is organized into three main sections. First, preliminary speed profile and workload profile models, which have been reported elsewhere, are reviewed. Next, the microcomputer procedure for using these models is described. Last, recommendations are made for further development of both the preliminary models and the procedures for using them.

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PRELIMINARY MODELS FOR EVALUATING CONSISTENCY

Conceptual Framework

The causes and consequences of geometric inconsistencies are best explained within the context of driver-vehicle-roadway interactions. The driving task is principally an information-processing and decision making task. Driver workload is a principal measure of driver information processing and is defined as "the time rate at which drivers must perform a given amount of work of driving task" (*7*). The roadway geometry and other factors (including the roadside environment, weather, traffic control devices, traffic conditions, etc.) are the primary inputs to the driving task. The outputs are control actions that translate into vehicle operations that, in turn, can be observed and characterized by traffic measurements (e.g., operating speed).

Drivers generally devote sufficient attention to accommodation of the workload demands they expect of the roadway. Most rural highways have relatively low workload demands; therefore, drivers often have relatively low attention levels on them. Geometric inconsistencies, however, impose higher workloads and demand more attention than are typically required and, therefore, more than drivers expect. Drivers who recognize the disparity between their expectation and the actual workload requirements of a feature increase their attention level and appropriately adjust their speed or path. Drivers who fail to recognize or are slow to recognize the disparity may make speed or path errors that increase the likelihood of accidents. Therefore, abrupt speed or path changes are common manifestations of the unexpectedly high workload demands associated with geometric inconsistencies. In theory, geometric inconsistencies could be measured by either increases in driver workload requirements or decreases in operating speeds between successive features (*8*).

Operating Speed–Based Consistency Evaluation

Concerns about and procedures for evaluating consistency on rural two-lane highways have focused on horizontal curves. Curves have higher average accident rates than tangent sections (*9*), and average accident rates on curves increase as the required speed reduction from an approach tangent to a curve increases (*3*).

Most of the procedures for evaluating horizontal alignment consistency are based on operating speed reductions. Switzerland was probably the first country to incorporate into their design procedures a speed-profile model for evaluating speed reductions (*10*). Leisch and Leisch (*11*) were the first in the United States to publish an operating speed–based procedure for evaluating horizontal and vertical alignment consistency. Lamm et al. (*12*), Lamm and Choueiri (*13*), and Lamm et al. (*14*) played a significant role in renewing U.S. concerns about consistency considerations.

The speed profile model in the microcomputer program described in this paper has the same form as the Swiss model (*10*), uses the basic equations and assumptions reported by Lamm et al. (*14*), and was calibrated by Ottesen and Krammes (*2*). The speed profile model estimates the 85th percentile speed at each point along a horizontal alignment. This profile is used to calculate the decrease in 85th percentile operating speed from an approach tangent to a curve, which is the measure of consistency associated with a curve.

Calibrating the speed-profile model required three types of information:

- A regression equation for the 85th percentile speed on a horizontal curve as a function of curve geometry;
- The 85th percentile desired speed on long tangents, which is defined as the speed maintained by the 85th percentile driver on the portion of long tangents outside the influence of adjoining horizontal curves; and
- Deceleration and acceleration rates entering and departing curves.

The regression equation for 85th percentile speed on a horizontal curve was developed based on free-flow passenger vehicle speed data from 138 curves in five states (New York, Oregon, Pennsylvania, Texas, and Washington). The roadways on which data were collected were low- to moderate-volume rural collectors or minor arterials in level to rolling terrain (i.e., grades $\leq$ 5 percent). Other characteristics of the roadways included: design speed $\leq$ 100 km/hr (62.1 mi/hr), lane widths between 3.05 and 3.66 m (10 and 12 ft), and shoulder widths between 0 and 2.44 m (0 and 8 ft).

Twelve curve geometry, cross-section, and approach-condition variables were considered as predictors of 85th percentile speed on curves, and several equation forms were tested. The following multiple-linear regression model, with an R^2 value of 0.82, a root mean square error of 5.1 km/hr (3.1 mi/hr), and a P value of 0.0001; was recommended (*2*):

$$V85 = 102.45 - 1.54D + 0.0037L - 0.10I \qquad (1)$$

where

$V85$ = 85th percentile speed on the curve (km/hr),
D = degree of curvature (degrees),
L = length of curve (m), and
I = deflection angle (degrees).

The desired speed on long tangents was based on speed data from 78 approach tangents that were long enough for drivers to reach and maintain a maximum desired speed. Attempts to model the desired speed on long tangents using predictor variables, including tangent length, parameters of the adjoining curves, cross-section width, terrain type, and geographical region of the United States, were unsuccessful. Therefore, the model uses 97.9 km/hr (60.8 mi/hr), the mean of the 85th percentile speed on the 78 long tangents, as the desired speed on long tangents.

The speed profile model assumes that speeds are constant through horizontal curves and that deceleration and acceleration occur only on the tangents approaching and departing the curve. These assumptions are simplifications of reality; the research literature reports some results supporting these assumptions and other results suggesting that acceleration and deceleration occur within curves. The error in estimated speed reductions resulting from these simplifications, however, is likely to be small. Acceleration and deceleration rates are assumed to be equal. The 0.85-m/sec^2 (2.8 ft/sec^2) rate reported by Lamm et al. (*14*) was used in the model without validation. This rate is similar to the 0.8-m/sec^2 (2.6 ft/sec^2) rate assumed in the Swiss procedure (*10*).

The speed profile model uses basic equations of motion in combination with the calibration data (speeds on curves, speeds on long tangents, and deceleration and acceleration rates) to estimate the 85th percentile speed at each point along a horizontal alignment. The equations of motion are used to determine what speed could be attained on the tangent and over how much of the tangent deceleration and acceleration would occur so that the appropriate speed (estimated by Equation 1) would be reached on the horizontal curves and the desired speed on long tangents would not be exceeded.

Driver Workload-Based Consistency Evaluation

The use of driver workload as a measure of consistency has been much more limited than operating speed. Messer et al. (*7*) developed a model for estimating driver workload based on roadway geometry and incorporated it into a procedure for evaluating rural highway design consistency. Preliminary evaluations suggest that these workload estimates are good indicators of high accident locations on rural two-lane highways (*15,16*). The procedure is manual, however, and has had only very limited application.

One strength of driver workload as a measure of consistency is that, in theory, it can be applied to any geometric feature, unlike operating speed reduction, which is limited in application to horizontal, and possibly vertical, alignment. The principal weakness of driver workload is that it is difficult to measure. The Messer et al. model (*7*) is based on subjective appraisals rather than objective measurements, which makes it difficult to validate and, therefore, limits its credibility.

The workload profile model used in the microcomputer procedure described herein was developed by Shafer et al. (*17*). To address the criticism about the subjective basis of driver workload estimates, they used the vision occlusion method, which is an objective method for measuring driver workload.

In the vision occlusion method, drivers voluntarily occlude their vision, opening their eyes only when they think it necessary to extract information for the guidance task. If vehicle speed is constant and lane integrity is not violated, then the amount of time that drivers are unwilling to have their vision occluded over a fixed length of roadway represents the mental workload required for the guidance task. Workload is defined as the proportion of total driving time that drivers need to look at the roadway. The lower the information-processing demands for guiding the vehicle along the roadway, the longer the drivers will voluntarily keep their vision occluded. Conversely, the greater the information-processing demands, the more a driver will need to look at the roadway and thus the higher the mental workload.

Calibrating the workload profile model requires two types of information: a regression equation for driver workload on a horizontal curve as a function of curve geometry and driver workload on tangents.

The vision occlusion method was used to measure driver workload on curves (without superelevation) and tangents on test courses laid out on former airport runways at the Texas A & M Proving Ground Research Facility. Selected degrees of curvature (3 degrees, 6 degrees, 9 degrees, and 12 degrees) and deflection angles (20 degrees, 45 degrees, and 90 degrees) were studied. Shafer et al. (*17*) describe the test method in detail. For each curve and tangent, the workload measurements of all subjects were averaged. A total of 55 subjects participated in the tests.

A regression equation was developed for the average workload on curves. Degree of curvature and deflection angle were tested as predictor variables. The following simple-linear regression equation for average workload as a function of degree of curvature was recommended:

$$WL = 0.193 + 0.016D \tag{2}$$

where WL is the average workload of curve and D is the degree of curvature (degrees).

This equation had an R^2 value of 0.90, a root mean square error of 0.020, and P value of 0.0001. Driver workload on curves increases approximately linearly with increasing degree of curvature.

The mean of the workload observations on tangent sections of the test courses, 0.176, was used as the driver workload on tangents in the workload profile model. This value indicates that subjects required vision only 17.6 percent of the time on the tangent sections of the test courses.

The workloads measured are likely to be lower than would be experienced by drivers on an actual highway. The test courses were flat, and nothing in the environment beyond the courses required the subjects' attention. The workload estimates are considered a relatively pure measure of the workload demands of the guidance task of path-following on curves and tangents.

The current form of the workload profile model is very preliminary. The model consists only of the mean workload value on tangents and the workload estimates from Equation 2 for curves. Workload changes abruptly at the beginning and end of a curve. The gradual transitions in workload that were observed during data collection have not been represented in the model.

MICROCOMPUTER PROCEDURE FOR USING PRELIMINARY MODELS

The Highway Geometric Design Consistency Program facilitates the use of these preliminary models for consistency evaluations of rural two-lane highway horizontal alignments. This menu-driven microcomputer program provides tabular screens for entering and editing input data and creates output files of model results that can be presented in tabular or graphical form. The program is available in both metric- and English-units versions (*6,18*). The hardware requirement is an IBM-compatible, DOS-based microcomputer with a minimum of 270K RAM.

The data for which the models were calibrated limit the scope of the consistency evaluations that can be performed using the program to horizontal alignments consisting of horizontal curves and tangents on rural two-lane highways with design speeds ≤ 100 km/hr (62.1 mi/hr) in level to rolling terrain. There is no provision for evaluating transition curves. The speed profile model applies to horizontal radii ≥58 m (190 ft) and vertical grades ≤5 percent. The workload profile model applies to horizontal radii ≥145 m (476 ft) and deflection angles ≤90 degrees.

Input Data

The data requirements to perform consistency evaluations using the metric units version of the program are modest: stationing of the PC and PT of each horizontal curve, radius of each curve, and station equations. These data can be obtained from standard roadway plans.

Figure 1 is the tabular input data screen. By way of example, data for an 8-km section of rural two-lane highway in Texas have been entered and are shown on the screen.

The screen includes columns for:

- Curve number (in consecutive order);
- PC station (in metric stationing notation);
- PT station (that should be used in calculating the curve's length);
- Station equation (i.e., the PT station that should be used in calculating the subsequent tangent's length);
- Radius in meters;
- 85th percentile speed in km/hr (calculated automatically by the program using the regression equation for 85th percentile speeds on curves in the speed profile model based on the radius that has been entered); and
- Drive workload (calculated automatically by the program based on the regression equation for driver workload on curves in the driver workload profile model based on the radius that has been entered).

Output

The procedure provides both tabular and graphical output of the measures of consistency and profiles of 85th percentile speed and workload. Figure 2 shows the form of the procedure's tabular output from the speed and workload profile models. The output corresponds to the input data in Figure 1. For each curve, the tabular output indicates the estimated reduction in 85th percentile speed and the increase in driver workload from the approach tangent to the curve. These measures of consistency are computed from the speed profile and workload profile that are illustrated graphically in Figures 3 and 4, respectively.

Both Figures 3 and 4 have two parts. The top part is a bar chart depicting the sharpness of each horizontal curve along the alignment. The height of a bar represents the radius of the curve in meters; the higher the bar, the smaller the radius and, therefore, the sharper the curve. The width of a bar represents the length of curve in kilometers. The bottom part of the graphical output is either the speed profile or the workload profile. On the speed profile in Figure 3, the horizontal elements represent speed on a curve or on the portion of a long tangent on which the 85th percentile desired speed is attained; the diagonal lines represent deceleration and acceleration on the tangent approaching and departing a curve. The workload profile in Figure 4 illustrates the increase in workload on a curve relative to the base workload value of 0.176 for tangents.

Designers can use the 85th percentile speed profile to check the appropriateness of their design speed selections and to identify probable locations of operating speed inconsistencies that may

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File Edit Graphics Output Help

ALIGNMENT DATA

Curve No	PC Station	PT Station	Station Equation	Radius (m)	85 %-ile Speed (km/h)	Driver Workload
1	20.39	188.18		158.76	80.91	0.37
2	214.67	402.58		873.19	97.83	0.23
3	765.62	842.34		873.19	97.83	0.23
4	1+990.40	2+052.21		291.06	92.42	0.29
5	2+344.27	2+523.71		1746.38	97.83	0.21
6	3+589.41	3+723.34		145.53	79.71	0.39
7	3+772.05	3+899.97		145.53	79.88	0.39
8	4+635.36	4+742.04		1746.38	97.83	0.21
9	4+850.95	4+978.75		349.27	93.90	0.27
10	5+168.00	5+333.48		436.59	95.86	0.26
11	5+697.90	6+162.72		1746.38	97.83	0.21
12	6+464.59	6+639.33		582.12	97.83	0.24
13	6+999.79	7+184.38		582.12	97.83	0.24
14	7+326.44	7+508.65		582.12	97.83	0.24
15	8+031.99	8+124.96		291.06	92.17	0.29

F1:Ins Rec F2:Del Rec Esc:Exit

Edit current data. .\FM1179.DAT

FIGURE 1 Input data screen.

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.\FM1179.OUT Page: 1/ 1

**** Consistency Measures for .\fm1179.OUT **** Page - 1

Curve No	PC Station	Radius (m)	85 %-ile Speed Reduction (km/h)	Workload Increase
1	20.39	158.76	0.00	0.20
2	214.67	873.19	0.00	0.05
3	765.62	873.19	0.00	0.05
4	1+990.40	291.06	5.41	0.11
5	2+344.27	1746.38	0.00	0.03
6	3+589.41	145.53	18.12	0.21
7	3+772.05	145.53	3.22	0.21
8	4+635.36	1746.38	0.00	0.03
9	4+850.95	349.27	3.93	0.10
10	5+168.00	436.59	1.97	0.08
11	5+697.90	1746.38	0.00	0.03
12	6+464.59	582.12	0.00	0.07
13	6+999.79	582.12	0.00	0.07
14	7+326.44	582.12	0.00	0.07

PgUp:PrvPg PgDn:NxtPg ^X:ScrlUp ^Y:ScrlDn Esc:End

FIGURE 2 Tabular output screen.

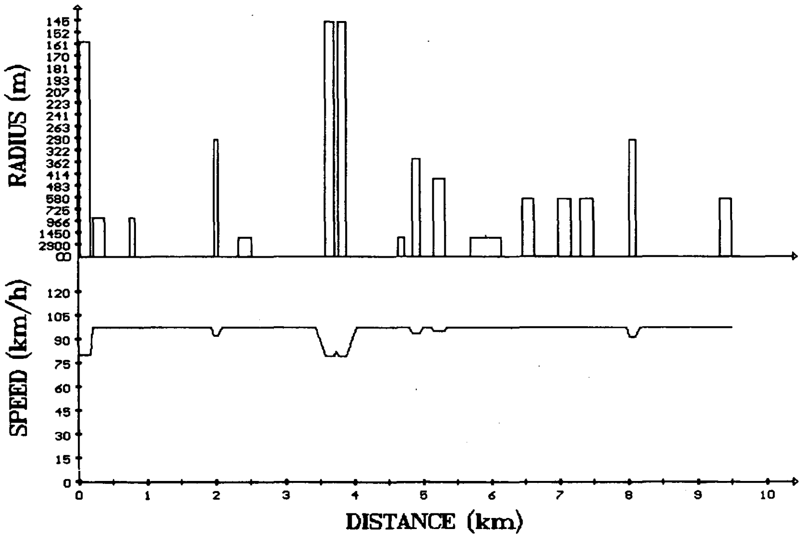

FIGURE 3 Graphical speed profile output screen.

require special attention in the design process. Statistical analyses indicate that the speed reduction estimates from the model are good indicators of accident potential on horizontal curves, with expected accident rates increasing approximately linearly as the estimated speed reduction increases (*3*). Leisch and Leisch (*11*) and Lamm et al. (*14*) have suggested that required speed reductions between successive alignment elements should not exceed 16 to 20 km/hr (10 to 12 mi/hr). If greater speed reductions are estimated, then accident experience should be checked to determine what safety improvements, if any, are warranted.

In summary, the microcomputer program provides an easy-to-use, menu-driven procedure for performing consistency evaluations of rural two-lane highway horizontal alignments using preliminary speed and workload profile models. Both tabular output of measures of consistency for each horizontal curve along an alignment (including the reduction in 85th percentile speed and increase in workload from the approach tangent to each curve) and graphical output (including speed and workload profiles) are provided.

RECOMMENDED FUTURE DEVELOPMENTS

Although the speed profile model is at a more refined stage than the driver workload model, both are considered preliminary models that require further development. Furthermore, the menu-driven microcomputer procedure is intended for interim use until the consistency module is implemented in the Interactive Highway Safety Design Model.

Speed profile models similar to the one described herein have been used for many years in other countries; therefore, the basic approach and assumptions are probably reasonable. Furthermore, the speeds on curves and on long tangents have been calibrated

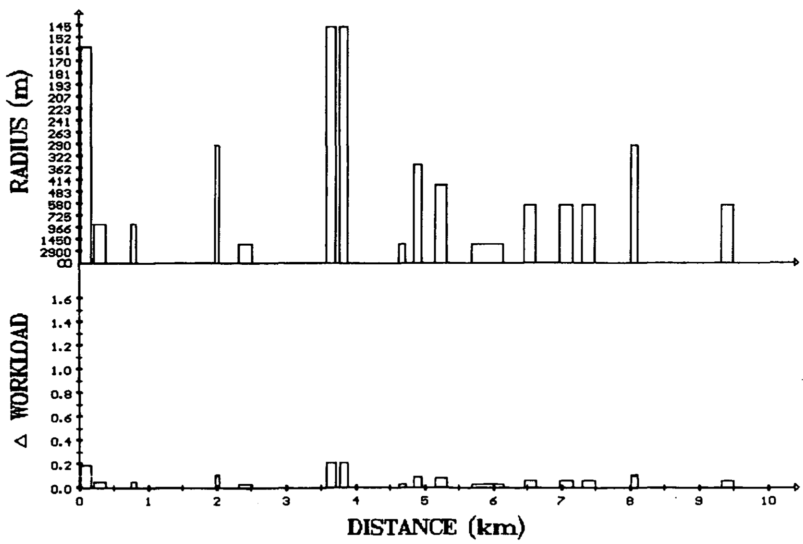

FIGURE 4 Graphical workload profile output screen.

using a moderately large data base of 138 curves and 78 of their approach tangents in five states representing three regions of the United States. The data are believed to be representative of relatively isolated horizontal curves (i.e., with relatively long approach tangents and sight distance) on typical state-maintained rural, two-lane collectors and minor arterials with design speeds $\leq$100 km/hr (62.1 mi/hr) in level to rolling terrain (i.e., with grades $\leq$5 percent). However, additional validation of the model is recommended to determine its accuracy for alignment conditions and geographical regions different from those for which the model was calibrated. Validation is also recommended on the assumptions about deceleration and acceleration rates: that is, that the rates are equal to 0.85 m/sec^2 (2.8 ft/sec^2), and the deceleration and acceleration occur only on the tangents approaching and departing the curve. Furthermore, consideration should be given to enhancing the model to account for other factors that may influence operating speeds, including vertical alignment, at-grade intersections, and changes in cross-section, and to estimate speed profiles for heavy vehicles as well as passenger cars. Additional analysis is also required to establish guidelines on desirable or absolute maximum speed reductions between successive geometric features and between vehicle types.

The workload profile model is very preliminary. It was calibrated based on data for 55 subjects on curves without superelevation on test courses that simulate actual roadways but lack such roadways' richness of visual inputs to drivers. It is recommended that the model be validated using data obtained with the vision occlusion method on actual roadways. It is also recommended that the model be refined to reflect more accurately the gradual transitions that occur in workload (much as they occur in speeds) approaching and departing curves. Finally, consideration should be given to applying the vision occlusion method for measuring driver workload to other geometric features (e.g., at-grade intersections and narrow bridges) that exhibit higher-than-average accident experience.

The menu-driven microcomputer procedure is an easy-to-use interim tool that can be used until the Interactive Highway Safety Design Model is completed. The consistency module in this model should, as planned, extract the required input data automatically from the data base of the commercial CAD package integrated with the model.

Previous research and experience in other countries suggest that consistency evaluations of rural two-lane highways with design speeds less than 100 km/hr (62.1 mi/hr) can promote the design of safer alignments. Implementation of consistency evaluations in U.S. design practice may have been slowed, in part, by the lack of easy-to-use procedures. It is hoped that the microcomputer procedure reported herein will encourage experimentation with the preliminary models for consistency evaluation so that the state of the art in the United States can be improved and, in time, enhanced models can be incorporated as a consistency module in FHWA's Interactive Highway Safety Design Model.

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