Comparison of Different Procedures for Evaluating Speed Consistency

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The need for achieving operating-speed consistency on two-lane rural highways through consistent horizontal alignment is discussed. One American and two European methods for evaluating horizontal alignment consistency are compared: a graphical speed-profile technique proposed for use in the United States, a theoretical speed model utilized by the Swiss highway design community, and a German procedure using a design parameter known as the curvature change rate. The results of the comparison of the three approaches show that although at times substantially different speed values are obtained from each method, the fundamental results necessary to evaluate alignment consistency are basically the same. On the basis of this comparison, it appears that the curvature-change-rate method is the most convenient for predicting changes in operating-speed profile along a rural roadway brought about by inconsistencies in horizontal alignment.

According to Cleveland et al. *(1)*,

> Two-lane rural highway safety is an issue of pressing national concern. It has been identified as the highest priority research need in the area of responsibility of the TRB Committee on Geometric Design. These roads constitute approximately 4 million km (2.5 million miles) or 63 percent of the highways in the United States and are the locations of about 50 percent of all highway fatalities. They have the highest accident rate of any class of rural highway, with fatal and injury vehicle-mile exposure accident rates (VMER) consistently being four to seven times higher than those on rural interstate highways.

More than 60 percent of the total accidents and about 80 percent of the fatalities on two-lane rural highways may be indirectly attributed to improper speed estimation. Although human factors may be identified as a major cause in all accidents, the driver's frame of mind and physical condition are virtually impossible to control from a design standpoint. Besides alcohol abuse, absence of seat-belt use, and poor judgment at intersections, most of the errors due to excessive speed occur with reference to road design. Young drivers aged 15 to 24 are especially endangered, in large part because of their lack of driving experience. This age group represented about 36 percent of all fatalities in the United States in 1982 *(2–6)*.

Many of these speed errors may be related to inconsistencies in horizontal alignment that cause the driver to be surprised by sudden changes in the road's alignment, to exceed the critical speed of a curve, and to lose control of the vehicle. These inconsistencies can and should be controlled by the engineer when a roadway section is designed or improved *(7, 8)*.

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Many experts believe that abrupt changes in operating speed lead to accidents on two-lane rural roads and that these speed inconsistencies may be largely attributed to abrupt changes in horizontal alignment *(9–12)*. Approximately $2 billion from federal and state sources is spent annually on the resurfacing, restoration, and rehabilitation of two-lane rural roads in the United States. This program is intended to extend the useful service life of these highways without the addition of many costly geometric redesigns. New designs and major reconstruction are not included in this significant expenditure *(13)*. Considering the magnitude of this annual investment, it is clear that a convenient method for locating alignment inconsistencies would provide a first step in the improved allocation of these resources by identifying the need for improved horizontal alignment. Providing longer road sections with relatively consistent alignment and thereby a consistent driving behavior is an important step in reducing critical driving maneuvers, thereby obtaining less hazardous road sections and enhancing traffic safety on two-lane highways.

Methods to improve highway alignment consistency have existed in several western European countries for more than the last decade. Similar procedures have been proposed for use in the United States but are not yet considered standard. One American and two European methods are discussed in the following pages: an operating-speed concept proposed by Leisch and Leisch *(9)*, a theoretical speed model used in the Swiss design standard *(14, 15)*, and a German design procedure related to a parameter known as the curvature change rate *(15–18)*.

BACKGROUND

Many studies have been conducted that focus on obtaining a more consistent design and the effect of inconsistencies on traffic safety. A survey of the literature by Hayward *(12)* suggests that easing a few sharp curves may have a much greater effect on safety improvement than easing more gentle curves.

Among other results, the following statement was made by the New York State Department of Transportation in 1983 *(19)*:

> Among improvement types showing large accident reductions and fair safety benefit cost ratios are horizontal alignment changes. Horizontal alignment improvements at 15 sites resulted in overall accident reductions of 45 percent and fatal/injury accident reductions of 42 percent. Efforts must be made to bring as many two lane rural roads to an acceptable level of operating speed consistency as possible.

The increased use of operating speed as a preferred criterion over design speed was also noted in the 1977 AASHTO Guidelines for resurfacing, restoration, and rehabilitation

(RRR) projects *(20)*: "The desirable design should accommodate the current running speed and a minimum design speed should not be established."

ALTERNATIVE DESIGN STRATEGIES

Efforts to define a systematic process for evaluating horizontal design and its subsequent impact on operating-speed profiles have been proposed for the United States; such a process is in use in Switzerland and Germany. Each is briefly described in the following sections.

Leisch Method *(9)*

Leisch and Leisch have suggested that using design speed alone as the control for design may lead to undesirable geometry. Even though design speed has been used for several decades to determine allowable horizontal alignment, it is possible to design certain inconsistencies into highway alignment. At low and intermediate design speeds, the portions of relatively flat alignments interspersed between the controlling curvilinear portions may produce operating-speed profiles that may exceed the design in the controlling sections by substantial amounts.

To overcome this weakness in current practice, Leisch and Leisch have suggested a new concept in the definition and application of design speed. The overall objective is to design for driver expectations and to comply with inherent driver characteristics to achieve operational consistency and improve driving comfort and safety.

The Leisch method involves using a speed-profile technique to achieve consistency in the horizontal and vertical alignments. They suggest the use of the "10-mph rule" as a design principle applied in specific situations as follows:

- Within a given design speed, potential average passenger-car speeds generally should not vary more than 10 mph (~16 km/hr).
- A reduction in design speed, where called for, normally should not be more than 10 mph.
- Potential average truck speeds generally should not be more than 10 mph below average passenger-car speeds at any time on common lanes.

This procedure consists of determining the average running speeds on horizontal curves in accordance with the low-volume relations of average running speed to design speed contained in the AASHTO guidelines *(21, 22)* and combining these with a series of nomographs to determine the amount of acceleration and deceleration for passenger cars and trucks. Both the horizontal and vertical alignments are taken into consideration, and a resulting speed profile is developed for the road section. Comparing the speed profile with the 10-mph rule, inconsistencies in the profile may be located and the design may be adjusted to eliminate them. The Leisch method is one of the first methods developed in the United States that may be used for evaluating consistency in the horizontal and vertical alignments of a roadway. A more detailed discussion and an example of this procedure will be given later in this discussion.

Swiss Method *(14, 15)*

The design speed concept as it is defined in Switzerland is not directly comparable with that used in the United States. Because the level of design and construction of a certain type of road is not fixed in Switzerland, ranges of design speed are assigned to each road type. Criteria that must be considered by the designer when a design speed is selected include the importance of the road, the traffic volume and mix, and the characteristics of the topography. The selected design speed is then used to determine minimum design values in a manner similar to that found in U.S. guidelines.

However, in addition to the design speed concept, the Swiss use a theoretical speed model to analyze the consistency of the horizontal alignment. This procedure is similar to the Leisch method in that it utilizes a speed-profile diagram to detect abrupt changes in what the Swiss determine to be the project speed. (Project speed is comparable with operating speed in the United States).

The project speed is modeled from geometric design of the horizontal and vertical alignments. It is expected to predict the maximum speed to be found on a certain roadway section. This project speed (not design speed) serves as a test speed to assess adequate sight distances and to evaluate adequate superelevation rates in cases when the project speed is higher than the design speed.

Standard values for the project speed have been determined through field research and are tabulated for different radii. The speed is considered constant over the length of the curve. Changes in the project speed between two successive curves, or between a curve and a tangent, are normally not allowed to exceed ~12 mph (20 km/hr), but for project speeds of less than 45 mph (70 km/hr) a speed change of less than ~6 mph (10 km/hr) is desirable.

The Swiss have developed a formula for calculating the "transition length," which is the distance required for acceleration or deceleration of a vehicle as it approaches or leaves a curve based on the speed difference between two curves or between a curve and a tangent. Unacceptable ranges for these transition lengths are also tabulated.

A speed diagram is used to graphically locate inconsistencies in the speed profile and thereby inconsistencies in the horizontal alignment. Because the Swiss make several simplifying assumptions, this method is easy to use and similar conceptually to the Leisch method. A more detailed discussion of this procedure and an example illustrating its use will be given in the next section.

German Method *(15–18)*

Highway design speed as applied in Germany depends on many issues, including environment and economic conditions, function of the road network, travel purposes, quality of traffic flow, road category, topography, and so on. As in the United States, the design speed is used to determine minimum design values. The Germans acknowledge that the design speed influences many roadway characteristics and therefore decisively affects traffic safety, quality of the traffic flow, and the local economy. German practice requires that constant design speed be applied to long lengths of road sections or particular roadway classifications.

In addition to the design speed, German designers use operating speeds to control design standards. The operating speed as defined in Germany corresponds to the 85th-percentile speed of passenger cars under free-flow conditions for clean, wet road surfaces. Because the 85th-percentile speed is normally higher than the design speed, the operating speed is a value used instead of design speed to determine adequate superelevation rates and necessary stopping sight distances. Use of this higher value builds in an additional factor of driving safety for roadway elements.

In contrast to the Leisch and Swiss methods, a different approach toward achieving consistency in horizontal alignment is taken in the German design guidelines. Instead of working with single curves and speed profiles, the Germans use a parameter called "curvature change rate" (CCR) to describe overall roadway homogeneity and to prevent abrupt (and unsafe) transitions in operating speeds between local homogeneous sections of roadways. CCR is defined as the absolute sum of the angular changes in the horizontal alignment divided by the length of the highway section.

It has been found through field observations in Germany that the operating speed remains relatively constant over the length of sections with similar characteristics and that this operating speed is strongly correlated to CCR *(7, 18, 23)*. Lengths and radii of all circular curves and lengths of all transition curves and tangents within the section may be used to compute CCR. A nomograph relating CCR to operating speed may be used to predict the operating speed of the section.

Currently, German design guidelines *(16)* require that the predicted operating speed within any given section not exceed the design speed of that section by more than ~12 mph (20 km/hr). Furthermore, a limit on the permissible section-to-section difference in the operating speeds not to exceed ~6 mph (10 km/hr) ensures operational consistency and provides a balanced design. If these conditions are not met for any particular section, the design of the horizontal alignment must be adjusted.

A more detailed discussion and an example illustrating the use of the procedure will be given in the next section.

EVALUATING OPERATING-SPEED CONSISTENCY

The differences among the speed-profile techniques of Leisch, the Swiss, and the Germans are interesting to compare. Example applications of the three methods on a single roadway section (Figure 1) demonstrate the difference in how each is used to identify operating-speed inconsistencies. The common example roadway shown in Figure 1 is a two-lane main primary rural road with lanes 10 ft wide, and for simplicity it is assumed that the vertical alignment of the entire section is level. The alignment before point *A* traveling west to east is assumed to be a long tangent section. Only the operating-speed profiles for passenger cars will be constructed.

Example of Leisch Method

The basic characteristics of the speed-profile technique proposed for use in the United States are as follows:

1. The profile is based on low-volume free-flow conditions, using the average running speeds of traffic under favorable roadway conditions (daylight, good weather, etc.).
2. The top average running speed of passenger cars for a given highway type may be found in Table 1. These speeds are based on open, near-level, and straight highways outside the influence of any other geometric constraints.
3. The average running speeds through horizontal curves are taken from Figure 2, which was developed according to low-volume relations of average running speed to design speed adapted from the 1965 AASHO geometric design policy *(21)*.
4. Deceleration and acceleration distances have to be taken from additional nomographs that were adapted and extrapolated from the 1965 AASHO guidelines for acceleration and deceleration at intersections and interchanges *(21)*.

By using Table 1 and Figure 2 of the Leisch method *(9)*, the following information may be determined:

- Top average speed for the highway: 60 mph (100 km/hr) (Table 1)

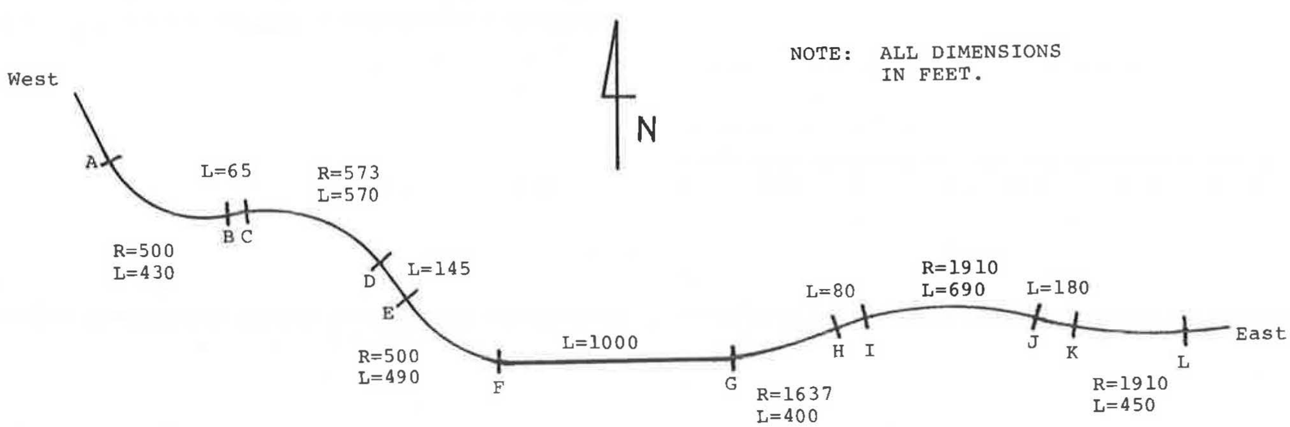

FIGURE 1 Horizontal alignment of roadway section to be examined for operating-speed consistency.

TABLE 1 TOP AVERAGE SPEED OF PASSENGER CARS ON VARIOUS TYPES OF HIGHWAYS FOR USE IN LEISCH METHOD *(9)*

Type of Facility	Highway Quality and Condition: Favorable		Moderate	
	mph	(km/h)	mph	(km/h)
Rural Highways				
Interstate	65	(100)	60	(95)
Primary - Main	60	(95)	55	(90)
Primary - Intermediate	55	(90)	50	(80)
Secondary	50	(80)	45	(70)
Urban Highways				
Interstate	60	(95)	55	(90)
Arterial - Main	50	(80)	45	(70)
Arterial - Intermediate	45	(70)	40	(65)
Secondary	40	(65)	35	(55)

Representative of low-volume, free-flowing conditions on open, near level and straight highways.

- Speed of Curve *AB*: 37 mph (~60 km/hr) (Figure 2)
- Speed of Curve *CD*: 39 mph (~60 km/hr) (Figure 2)
- Speed of Curve *EF*: 37 mph (~60 km/hr) (Figure 2)
- Speed of Curve *GH*: 58 mph (~90 km/hr) (Figure 2)
- Speed of Curve *IJ*: 60 mph (Figure 2)
- Speed of Curve *KL*: 60 mph (Figure 2)

Because this method uses a sophisticated technique for determining acceleration and deceleration distances, certain assumptions have to be made about speed reductions approaching a curve, sight distances, and topography (in this case, level terrain) when these nomographs are used *(22)*. These assumptions will not be discussed in detail in this paper, but it should be noted that different users of this procedure may arrive at slightly different values. However, the basic form of the speed profile will remain approximately the same; it is shown in Figure 3 for west–east travel and Figure 4 for east–west travel.

On examination of Figure 3 (west–east travel) it may be seen that there is an unacceptable break in the operating speed at point *A*. The speed difference is 23 mph (60 mph – 37 mph), which is greater than the recommended limit of 10 mph for this method. Also noticeable from the diagram is that the distance required to accelerate from 37 mph to 60 mph is longer than the remaining length of the section, points *F* to *L*. More information is necessary about the alignment after point *L* to determine whether the assumed maximum speed of 60 mph will actually be reached.

It should be noted that the speed profile in Figure 3 is valid

IMPERIAL UNITS

V-DESIGN SPEED, MPH	30				40				50				60			70			80
CORRESPONDING AVERAGE RUNNING SPEED, MPH																58	60	62	64
													52	54	56	58	60	62	64
									44	46	48	50	52	54	56	58 →			
					36	38	40	42	44	46	48	50	52	54 →					
	28	30	32	34	36	38	40	42	44	46	48 →								
D_C-MAX. DEGREE OF CURVE*	23.0	19.1	16.4	14.1	12.5	10.8	9.5	8.5	7.5	6.8	6.2	5.6	5.0	4.5	4.0	3.5	3.1	2.8	2.5
R_C-MIN. RADIUS, FEET	250	300	350	400	460	530	600	680	760	840	930	1030	1140	1280	1440	1630	1820	2030	2240

PERMISSIBLE AVERAGE RUNNING SPEEDS ON CURVES OF GIVEN RADII AT LOW-VOLUME, FREE-FLOW CONDITIONS - APPLICABLE TO PASSENGER CARS

*D_C = 5729.5780 ÷ R_C (Based on central angle subtending 100-foot arc)

Tabular values are based on an average maximum superelevation rate of .08

→ For a designated or estimated design speed, any larger radii beyond the arrow are assumed to have the same average running speed as at the arrow.

FIGURE 2 Speed-curvature relationships for use in Leisch method *(9)* [adapted from AASHO guidelines *(21)*].

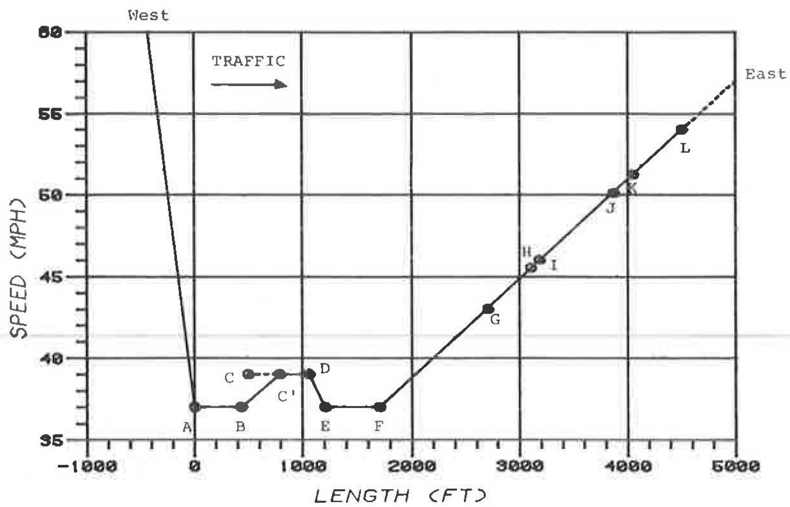

FIGURE 3 Speed profile resulting from application of Leisch method on roadway section of Figure 1 for west–east travel.

only for the direction of travel shown, because the acceleration and deceleration rates are different. Therefore, in order for the analysis to be complete, this same procedure must also be used to construct a similar speed diagram for the east–west direction of travel (Figure 4). In this direction, a speed difference of 22 mph (59 mph – 37 mph) occurs between points *G′* and *F*, which also exceeds the 10-mph limit.

By using this procedure, the speed changes before point *A* for west–east travel and point *F* for east–west travel are identified as critical areas in which the horizontal alignment causes an inconsistency in the speed profile. These critical locations should be investigated further to determine whether any corrective action should be taken.

Example of Swiss Method

Switzerland employs a speed model to examine consistency in horizontal alignment and to recognize dangerous breaks or transitions in the speed profile brought on by changes in horizontal alignment. The speed model represents the theoretical course of the project speed as a function of horizontal curvature. Several assumptions are made to simplify the procedure considerably, including the following:

1. The driver selects the project speed for a curve on the basis of the radius of the curve, and this speed is considered to remain constant throughout the curve. The project speed for any given radius may be taken from Table 2. For radii falling between the values in the table, the higher value should be chosen (not interpolated). Also, the horizontal lines in the table indicate the maximum allowable speed corresponding to the speed limit for each type of road. For example, rural roads have a maximum speed of 62 mph (100 km/hr).
2. The speed in tangents and transition curves corresponds to the posted speed limit (the horizontal lines in Table 2).
3. Decleration ends at the beginning of the circular curve.
4. Acceleration begins at the end of the circular curve.

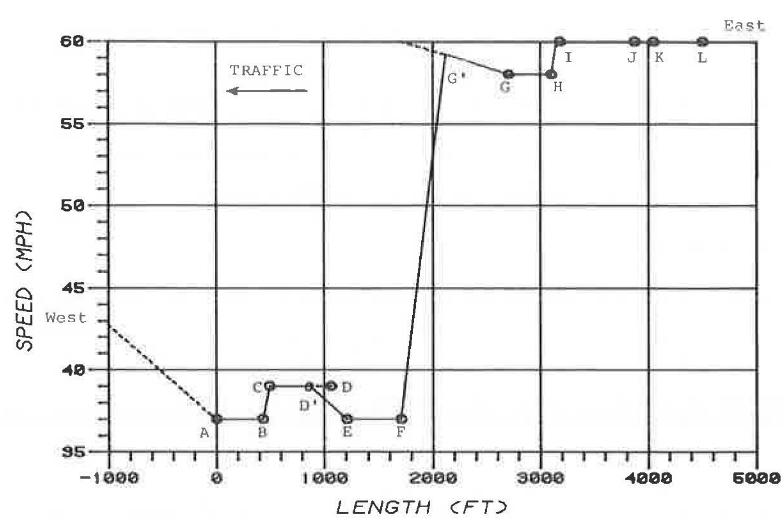

FIGURE 4 Speed profile resulting from application of Leisch method on roadway section of Figure 1 for east–west travel.

TABLE 2 RELATIONSHIP BETWEEN RADII AND PROJECT SPEED FOR USE IN SWISS METHOD *(14, 15)*

Radii [m]	Radii [ft]	Project Speed [km/h]	Project Speed [mph]	
45	148	40	25	
60	197	45	28	Urban
75	246	50	31	Roads
95	312	55	34	
120	394	60	37	
145	476	65	40	
175	574	70	43	
205	672	75	46	
240	787	80	50	Rural
280	918	85	53	Roads
320	1050	90	56	
370	1214	95	59	
420	1378	100	62	
470	1542	105	65	
525	1722	110	68	
580	1902	115	71	Interstate
650	2132	120	74	
710	2329	125	78	
>780	>2558	130*	81	

*120 km/h since January 1, 1985.

5. Acceleration and deceleration are considered to be equal and constant at a rate of a = ~2.6 ft/sec^2 (0.8 m/sec^2); thus one speed diagram is sufficient for both directions of travel.

6. The distance traveled during acceleration and deceleration, known as the transition length, may be taken from Figure 5 by using the project speeds between two consecutive design elements for the transition between two curves or between a curve and a tangent.

Because the relationships between project speed and radius are given in Table 2, a theoretical speed profile with corresponding transition lengths from one design element to the other may be established. Limits of maximum differences in the project speeds and ranges of unallowable, or avoidable, transition lengths between successive design elements with different project speeds (Figure 5) ensure operational consistency and provide a balanced horizontal design.

Using the procedures and assumptions noted earlier, the speed profile in Figure 6 may be constructed, which is related to the horizontal alignment in Figure 1. From Table 2 the project speeds of Curves *AB*, *CD*, and *EF* are each found to be ~43 mph (70 km/hr), and in Curves *GH*, *IJ*, and *KL* the speeds are found to be the maximum value of ~62 mph (100 km/hr), which is the speed limit for rural roads in Switzerland. This is comparable with the top average running speed used in the Leisch method.

The required acceleration and deceleration lengths may be taken from Figure 5 when the appropriate project speeds are known. For the acceleration after point *F*, Vp_1 = ~43 mph (70 km/hr) and Vp_2 = ~62 mph (100 km/hr), so the required distance is approximately 800 ft (245 m); thus, a speed ~62 mph would be reached at point *F′*. This would also be the distance required for the deceleration before point *A*, because the speeds involved are the same in both cases. The transition length of 800 ft resulting from the two project speeds falls into the range of transition lengths that should be avoided (Figure 5) and would indicate that a transition between these two speeds would cause an inconsistency to occur.

The short tangent sections *BC* and *DE* produce only a negligible amount of acceleration, so the speeds in these sections are assumed to be the same as those on the curves surrounding them.

In addition, examination of Figure 6 reveals that speed breaks of 19 mph (62 mph − 43 mph) occur before point *A* for

V_{p1} (km/h) resp. V_{p2} / V_{p2} (km/h) resp. V_{p1}	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130
40																			
45	20																		
50	45	25																	
55	70	50	25																
60	95	75	55	30															
65	125	105	85	60	30														
70	160	140	115	90	65	35													
75	195	175	150	125	100	70	35												
80	230	210	190	165	135	105	70	35											
85	270	250	230	205	175	145	110	75	40										
90	315	295	270	245	220	185	155	120	80	40									
95	360	340	315	290	260	230	200	165	125	85	45								
100	405	385	360	335	310	280	245	210	175	135	90	45							
105	455	435	410	385	360	330	295	260	225	185	140	95	50						
110	605	485	465	440	410	380	345	310	275	235	195	145	100	50					
115	660	540	515	490	465	438	400	365	330	290	245	205	155	105	55				
120	615	600	575	550	520	490	460	425	385	345	305	260	210	165	110	55			
125	675	665	635	610	580	550	515	480	445	405	365	320	270	220	170	115	60		
130	740	715	695	670	640	610	580	545	505	465	425	380	335	285	230	175	120	60	

Transitions of project speeds that should be avoided are listed in the middle section of the nomograph

Not allowable ranges of decelerations are listed in the lower left section of the nomograph

FIGURE 5 Required transition lengths for acceleration and deceleration for use in Swiss method *(14, 15)*.

west–east travel and before point *F* for east–west travel. These values are greater than the suggested speed change limit of ~12 mph (20 km/hr) in the Swiss method. The critical sections identified through the Swiss procedure occur at the same locations as they do in the Leisch method.

However, several differences are immediately obvious between this technique and the Leisch method. First, the speed values in the first curved section (*AF*) are 4 to 6 mph higher in the Swiss method than those obtained from the Leisch method (see Table 3). Second, there is a substantial difference in the distances required for acceleration after point *F*. With the Leisch method the acceleration is not completed within the section being examined, whereas in the Swiss method acceleration ends before curve *GH* is reached. This is a major discrepancy between the two procedures, due in large part to the fact that both use theoretical acceleration rates, which should be tested under actual driving conditions. Therefore, determining accurate acceleration and deceleration rates should be the objective of a future study.

Example of German Method

German designers use different techniques to guide the design of horizontal alignment. These include policies that control successive curves, lengths of tangents, and consistency in horizontal alignment in addition to controls on CCR.

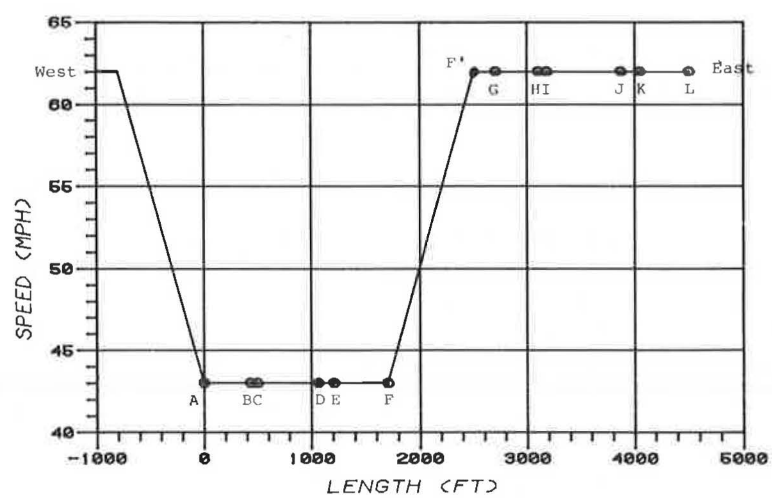

FIGURE 6 Speed profile resulting from application of Swiss method on roadway section of Figure 1 for both directions of travel.

TABLE 3 COMPARISON OF OPERATING-SPEED VALUES (MPH) OBTAINED FROM THREE METHODS

Method	Curve AB	CD	EF	GH	IJ	KL	
Leisch W-E	37	39	37	~44	~47	~53	mph
Leisch E-W	37	39	37	58	60	60	mph
Swiss	43	43	43	62	62	62	mph
German	41	41	41	51	51	51	mph

Nomographs in the design manuals provide guidance on safe combinations of successive curves. The radii of successive curves must fall within acceptable ranges, which increase as the curves become flatter.

Tangent sections between curves are limited by the design speed. The length of tangent (in meters) between two curves cannot exceed 20 times the design speed (in kilometers per hour) of that roadway. In this manner, long tangents are controlled and a curvilinear environment is encouraged.

Finally, the Germans use CCR to describe overall roadway characteristics and to prevent abrupt (and unsafe) transitions in operating speeds between long homogeneous sections of roadways. As previously mentioned, CCR is defined as the absolute sum of the angular changes in the horizontal alignment divided by the length of the highway section.

For a roadway section without transition curves, CCR may be expressed by the following formula (in metric units):

$$CCR = [\Sigma \mid L_i/R_i \mid (63.7)]/L \quad \text{(gon/km)} \qquad (1)$$

or in imperial units:

$$CCR = [\Sigma \mid L_i/R_i \mid (57.3)(2{,}640)]/L \quad \text{(degrees/half-mile)} \qquad (2)$$

where

L_i = length of curve i (ft),
R_i = radius of curve i (ft), and
L = total length of section (ft).

(Note: a *gon* is a unit similar to a degree but related to 400 divisions in a circle instead of 360.)

Use of the design parameter CCR is shown in Figure 7, taken from the German design guidelines *(16)*, with an additional scale added for imperial units. The figure shows the relationship between CCR and 85th-percentile speed and is used to predict the operating speed of any given homogeneous road section. These curves are based on regression analysis of data obtained from actual speed measurements conducted in Germany *(7, 23)*. The allowable speed change between any two consecutive homogeneous road sections is ~6 mph (10 km/hr), and this criterion is used to maintain consistency in the alignment.

To use this method, the first step is to divide the roadway being examined into subsections that have homogeneous alignments. The best way to do this is to construct a cumulative plot of the absolute sum of curvature (1/*R*) versus length for the entire section.

Figure 8 gives this plot for the example alignment in Figure 1. The dotted line represents the theoretical course of the curve if each subsection were perfectly homogeneous, that is, if each curve had exactly the same length and radius and there were no tangents present within the subsection. By comparing the theoretical curve with the actual curve, it is obvious that the road section should be divided into three subsections with nearly homogeneous horizontal alignments: *AF*, *FG*, and *GL*.

Once this has been done, the next step is to calculate the CCR of each subsection by using Equation 2:

Subsection *AF*:

$$CCR = \{[(430/500) + (570/573) + (490/500)] + (430 + 65 + 570 + 145 + 490)\}\ (57.3)\ (2{,}640)$$
$$= 252.2 \text{ degrees/half-mile}$$

Subsection *FG*:

$$CCR = [(1{,}000/\infty)/1{,}000]\ (57.3)\ (2{,}640)$$
$$= 0.0 \text{ degree/half-mile}$$

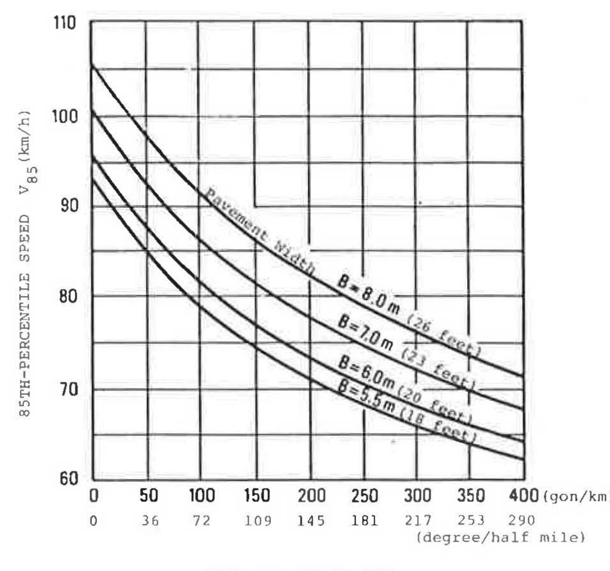

FIGURE 7 Relationship between CCR and 85th-percentile speed in the German guidelines *(16)*.

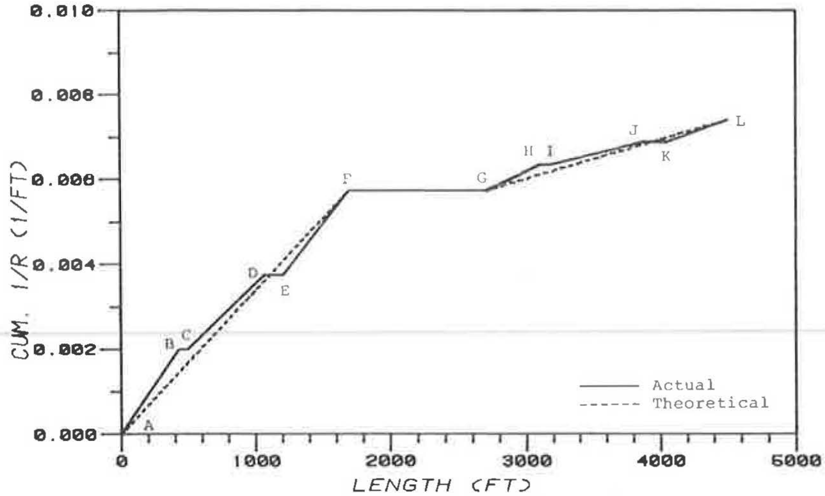

FIGURE 8 Determination of subsections with homogeneous horizontal alignments for roadway section of Figure 1.

Subsection *GL*:

$$CCR = \{[(400/1{,}637) + (690/1{,}910) + (450/1{,}910)] \div (400 + 80 + 690 + 180 + 450)\}\ (57.3)\ (2{,}640) = 70.7 \text{ degrees/half-mile}$$

Using these values and Figure 7 for 10-ft lanes (pavement width 20 ft), the 85th-percentile speed of each subsection may be determined:

- Subsection *AF*: V_{85} = 66 km/hr × 0.62 = 41 mph,
- Subsection *FG*: V_{85} = 96 km/hr × 0.62 = 60 mph,
- Subsection *GL*: V_{85} = 82 km/hr × 0.62 = 51 mph.

These values are valid for both directions of travel, because Figure 7 is based on speed measurements for both directions of travel.

These results indicate that the expected change in operating speed between subsections *FG* and *GL* would be approximately 9 mph, which is slightly over the very strict 6-mph German speed-change limit between successive subsections. Thus there may be a problem with the transition between these two subsections, but it is probably not very serious, especially considering that this value is within the limits recommended by the Leisch and the Swiss methods.

However, between subsections *FG* and *AF* the expected speed difference is approximately 19 mph, which is more than three times the limiting value used in Germany. This finding suggests that a severe inconsistency exists between these subsections. The transition should be investigated more thoroughly, especially considering the accident history of the section, to determine whether any action such as horizontal redesign may be warranted.

The curves in Figure 7 indicate clearly that the pavement width (lane width) of the roadway has an important effect on the operating speed. This example was conducted for a lane width of 10 ft (pavement width 20 ft); obviously different speeds must be expected for different lane widths. It should be noted here that in this comparison the German procedure is the only one that has the effect of lane width built in; the Leisch and the Swiss methods make no provisions for the effect of pavement width on operating speed.

RESULTS AND CONCLUSIONS

The various operating-speed and speed-change values obtained by using each of the three methods are summarized in Tables 3 and 4. Although the differences may be quite substantial at times, the basic conclusions that may be drawn about the investigated road section are the same with each method: the critical speed changes occur before point *A* for west–east travel

TABLE 4 OPERATING-SPEED CHANGES AT THE CRITICAL LOCATIONS OF THE ROAD SECTION IN FIGURE 1

Method	Speed Changes Prior to Point A (West-East)	Speed Changes Prior to Point F (East-West)	Recommended Speed Changes
Leisch	23 mph	22 mph	10 mph
Swiss	19 mph	19 mph	~12 mph
German	19 mph	19 mph	~6 mph

and before point *F* for east–west travel. Furthermore, it should be emphasized that all three methods produce critical changes in operating speeds larger than any of the maximum allowable speed changes recommended by the different procedures for different countries and continents. These critical values are relatively the same in all three cases, ranging from 19 mph (Swiss and German methods) to 23 mph (Leisch method) (Table 4). If the Leisch method were adapted to the new AASHTO policy on geometric design (Green Book) *(22)*, the critical changes in operating speeds for all three methods would be about the same.

The German CCR method produces the same basic results as those obtained by using speed-profile methods, and it has several advantages over these graphical techniques. The CCR method is based solely on speed measurements and thus reflects the actual driving behavior of motorists, whereas the speed profiles are based largely on theoretical considerations. Also, in their current form the speed-profile techniques have made no provision for the effect of lane width on operating speed.

It would appear that the CCR method would be the most convenient to use in the process of locating inconsistencies in horizontal alignment. It can be easily adapted to the American design system and provides a means of efficiently identifying changes in the operating speed along a highway. It can also be used in connection with RRR projects to locate inconsistencies in alignment transitions and to determine whether a proposed improvement will cause the new roadway section to be designed to a higher standard that is inconsistent with preceding or succeeding highway sections.

The need for a method for achieving consistency in highway operation is emphasized by several findings of an in-depth study team sponsored by the International Road Federation, who surveyed current geometric and pavement design practices in several European countries *(10)*:

- The countries visited place much greater emphasis on achieving consistency among design elements than is called for in U.S. practice.
- In most cases the effect of individual design elements on operating speed is the mechanism for determining design consistency.
- The use of design speed as a concept to be applied to individual elements appears to be diminishing in favor of operating-speed parameters.

Thus it appears that U.S. designers could improve the quality of their design by employing some rational process for predicting the effect of geometry on operating-speed profiles. Adjusting the designs to ensure smoother operating-speed profiles would appear to provide a safety benefit without major cost. In joining their German and Swiss counterparts, U.S. designers could maximize the effectiveness of the significant annual expenditures currently being invested in the U.S. two-lane rural road system through the RRR program. At the very least the procedures outlined in this paper could be used by agencies to identify problem locations and perhaps avoid RRR "improvements" that encourage higher operating speeds and in doing so create a more hazardous environment.

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Simulation of Truck Turns with a Computer Model

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Recent federal legislation allowing the use of longer and wider trucks will have a significant impact on California's existing roadway system. Many freeway ramps, for example, were designed over a decade ago to accommodate only the largest trucks legally in use at that time. Some of the larger trucks legalized by the new legislation are expected to encounter problems maneuvering through these interchanges. Local governments are also concerned because urban intersections designed many years ago simply cannot accommodate the offtracking of the new larger trucks. To assess the ability of the larger trucks to operate on California's existing roadway system, their offtracking characteristics must be carefully evaluated. In the past, engineers at the California Department of Transportation traditionally used a graphic instrument known as the Tractrix Integrator for simulating truck turns supplemented with a mathematical calculation of the maximum amount of offtracking. A computer model developed for analyzing and evaluating truck offtracking is described. Offtracking results from the computer simulation model are first compared with results derived from the Tractrix Integrator, field observations, and mathematical formulas. The computer model is then used to analyze the offtracking characteristics for several of the new, longer trucks. Finally, applications of the computer model to evaluate some special offtracking situations or problems are discussed.

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The 1982 Surface Transportation Assistance Act (STAA) allowed wider and longer trucks on the Interstate system and portions of the primary system. In 1983 California enacted conforming legislation (Assembly Bill 866). As a result of these legislative changes, a new generation of larger trucks has emerged. The evaluation of the maneuverability of these longer, wider trucks and their ability to operate safely on the roadway system is of prime importance.

PREVIOUS METHODS

Offtracking may be described as "the amount of variation between the path traversed by a following wheel as compared to the path of the preceding wheel" *(1)*. In this paper the center of the axles, rather than the wheels, is used as the reference point for measuring offtracking. Offtracking and related terms are shown in Figure 1.

In California, two methods—the Tractrix Integrator and mathematical formulas—have been used to analyze and evaluate offtracking. The Tractrix Integrator was used to produce