Recommendations for Evaluating Horizontal Design Consistency Based on Investigations in the State of New York

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To a large extent, critical driving maneuvers on two-lane rural highways can be related to vehicular speeds that are inconsistent with the roadway alignment presented to the motorist. A method for identification of horizontal alignments that create speed transition problems for the motorist and recommendations for correcting them, for example, through the resurfacing, restoration, and rehabilitation (RRR) program, may help to improve highway safety on this important portion of the road network. An analysis based on design, speed, volume, and accident data for 261 road sections of two-lane rural state routes in the state of New York established (a) the relationship among the German design parameter curvature change rate, the American design parameter degree of curve, and operating speeds of passenger cars for different lane widths; (b) the effect of additional design parameters and volume data on operating speeds; (c) the relationship between degree of curve and accident rate for all lane widths and vehicle types; (d) estimates of reasonable ranges of degrees of curve and the corresponding operating speeds for good, fair, and poor designs; and (e) recommendations for evaluating critical inconsistencies in horizontal alignment. By applying these recommendations, the highway engineer could control minor inconsistencies in highway alignment, and detect and correct major geometric defects, for example, in conducting RRR projects.

Achieving consistency in horizontal alignment, and thereby a consistent operating speed, is an important issue to be considered in the design and redesign of two-lane rural highways to avoid possibly critical driving maneuvers, which may in turn lead to unfavorable accident risks.

In a recent survey of current geometric design practices in Europe conducted by an in-depth study team sponsored by the International Road Federation *(1)*, the following principal findings and recommendations relating to the present subject were compiled:

- The countries visited place much greater emphasis on achieving consistency among design elements than is called for in United States practices.
- In most cases the effect that individual design elements have 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.
- Design guidelines for resurfacing, restoration, and rehabilitation (RRR) improvements should be developed that enable the designer to analyze the impact of the proposed improvements on the operating speed of the roadway.

Furthermore, in Project 1S, Design and Corrective Geometrics, conducted by the FHWA (1986), 43 original ideas were developed into 18 research need statements and placed into the priority categories of very important, important, and desirable. Under the eight very important issues, one statement, which is directly related to this research, is found:

- Development of guidelines and procedures to promote design consistency in highway geometric design.

In this connection, the 1984 AASHTO *Policy on Geometric Design of Highways and Streets (2)* recommends the following:

- Consistent alignment always should be sought.
- Sharp curves should not be introduced.
- Sudden changes from areas of flat curvature to areas of sharp curvature should be avoided.

Therefore, a method for identifying horizontal alignments that create speed transition problems for the motorist and recommendations for correcting them, for example, for new designs and redesigns in the case of RRR projects, may be valuable in possibly reducing the accident risk on this important portion of the road network. This need has led to the present investigation *(3)*.

Design speed concepts in the United States *(4–6)* and most western European countries have existed since the 1930s and have been mainly directed toward evaluating dynamic aspects of driving, such as calculating, for a given design speed, minimum radii of curves, superelevation rates, and necessary stopping sight distances. However, recent knowledge about driving behavior and traffic operations, as well as research experience about unfavorable design as related to accident spots and dangerous road sections, require more and more an update of the design speed concepts. In this connection, many experts feel that there may be at least three design criteria that deserve to be further looked into.

The first criterion, which was observed during the last decade, is based on the concept of achieving consistency in

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horizontal alignment. For instance, studies have shown that the design speed concept allows building in of critical inconsistencies into the horizontal alignment, for example, between the flatter and sharper portions of the highway, when controlling horizontal curves sometimes correspond to an arbitrarily selected design speed. In these cases, transition sections may exist, requiring unexpected critical speed changes from the driver that may in turn lead to hazardous driving maneuvers *(7–12)*.

The second criterion is based on harmonizing design speeds and operating speeds. For instance, studies have shown that the driving behavior on an observed road section often exceeds the design speed on which the original design of the road section was based by substantial amounts, especially at lower design speed levels *(7, 8, 10–15)*.

The third criterion is related to dynamic safety of driving. Most European countries have adopted the idea that, when differences between operating speeds and design speeds exist, superelevation rates and stopping sight distances should be based on the normally higher operating speeds (expressed as the 85th percentile speeds of passenger cars under free flow conditions) in order to have higher dynamic traffic safety built in *(11–15)*.

The second and third issues will be considered in this research, though major attention will be given to the issue of achieving consistency in horizontal alignment.

Definite procedures for evaluating alignment inconsistencies do not exist in the following reviewed design guidelines: United States *(2)*, France *(13)*, Great Britain *(14)*, and Sweden *(15)*. Systematic processes for evaluating horizontal design consistency and its subsequent impact on operating speeds have been proposed by Leisch and Leisch *(7)* for the United States, and are in use in the Federal Republic of Germany *(11, 16, 17)* and Switzerland *(12, 18)*. To prevent abrupt transitions in operating speeds between sections of roadway with dissimilarities in road characteristics or between two successive design elements, the following maximum allowable speed changes have been recommended for passenger cars:

Leisch design method *(7)*: $\Delta V \leq 10$ mph (16 km/hr)
German design guidelines, *(17)*: $\Delta V \leq 6$ mph (10 km/hr)
Swiss design standard *(12)*: ΔV 12 mph (20 km/hr)

A comparison of the three procedures for evaluating speed consistency with example applications was presented at the 65th Annual Meeting of the Transportation Research Board, sponsored by the Committee on Operational Effects of Geometrics *(19)*. It was concluded that all three procedures can be used successfully for locating inconsistencies in horizontal alignment. The German procedure, which appears to be the most practical one, is based solely on speed measurements reflecting the actual driving behavior of motorists and not solely on theoretical considerations. In present form, the speed profile techniques of Leisch *(7)* and the Swiss standard *(12)* have no provisions for the effects of lane width on operating speed.

Therefore, in continuation of the study *(19)* and based on other previous research *(3)*, the applicability of the German procedure was checked for use, as related to two-lane rural highway sections in the state of New York. Because the German method assumes similarities of road characteristics within a given road section *(19)*, this procedure may be difficult to introduce into overall American design practices. Therefore, it may be of interest to investigate whether a more appropriate method for identifying operating speed inconsistencies in horizontal alignment could be developed as a means of easier application in the United States.

To accomplish this, the initial step was the selection of two-lane rural road sections that were appropriate for the study.

DATA COLLECTION AND REDUCTION

From spring 1984 to spring 1986, state routes throughout northern New York State were investigated, and a sufficient number of two-lane rural roadway sections, normally consisting of a sequence of tangent-to-curve or curved-section-to-tangent sections, was located. Site selection was limited to sections with the following features:

1. Removed from the influence of intersections.
2. No physical features adjacent or in the course of the roadway that may create abnormal hazard, like narrow bridges.
3. Delineated and with paved shoulders.
4. No changes in pavement or shoulder widths.
5. Grades less than or equal to 5 percent.
6. Average annual daily traffic between 400 and 5,000 veh/day.

The selection process resulted in 261 road sections of two-lane rural state routes in the state of New York of varying degrees of curve [*DC*, degrees (°) of curvature per 100 ft], broken down by lane widths as follows *(3, 20, 21)*:

- Ten-foot lanes (85 sections used) produced a wide range of design elements, ranging from good to poor designs, with recommended speeds usually ranging from 25 to 50 mph. These sections included sections with no traffic warning devices and others with arrow signs and chevrons.
- Eleven-foot lanes (92 sections used) produced a range of design elements, ranging from good to fair designs with recommended speeds normally ranging from 30 to 50 mph. These sections included sections with no traffic warning devices and others with arrow signs.
- Twelve-foot lanes (84 sections used) represented good designs in most cases with recommended speeds ranging from 35 to 50 mph. They were often unequipped with any sort of traffic warning device.

The average section length was about 1 mi, thus nearly 300 mi of state route sections in the state of New York were investigated and approximately 15,000 mi were driven during the selection phase. The road sections selected provided the widest range of changes in horizontal alignment that could be found by observation or by actual information given by the New York State Department of Transportation (NYSDOT).

For each of the selected road sections, the following data were collected (Tables 1–4):

TABLE 1 ALIGNMENT AND VOLUME DATA FOR INVESTIGATED ROAD SECTIONS

SOURCE OF FUND: NATIONAL SCIENCE FOUNDATION LANE WIDTH: 11 FEET

SECTION NUMBER	COUNTY NUMBER	REFERENCE MARKERS	LENGTH OF SECTION	CURVATURE* CHANGE RATE	PAVEMENT CONDITION	SHOULDER WIDTH	SHOULDER CONDITION	AADT**
1	2	3	4	5	6	7	8	9
3-21	7504	1497-1504	3696'	132.0	GOOD	8.0'	GOOD	1400
3-22						8.0'		
3-23	7504	1506-1510	2112'	150.5	GOOD	8.0'	GOOD	1400
3-24						8.0'		
13-1	3204	3075-3080	2640'	95.0	VERY GOOD	6.0'	VERY GOOD	2000
13-2						6.0'		
13-3	3204	3093-3104	5808'	976.8	GOOD	6.0'	GOOD	2000
13-4						6.0'		
13-5	3204	3101-3111	5280'	153.1	GOOD	4.5'	GOOD	2000
13-6						4.5'		
14-1	3705	1043-1051	4224'	314.9	GOOD	4.0'	FAIR	1800
14-2						4.0'		
14-3				314.9		4.0'		1800
14-4						4.0'		
19-3	4103	1142-1156	7392'	259.5	GOOD	3.5'	FAIR	1900
19-4						3.5'		
19-5	4602	1262-1273	5808'	401.3	GOOD	3.0'	FAIR	1700
19-6						3.0'		
28-9	2209	1006-1014	4224'	125.1	GOOD	5.5'	GOOD	1400
28-10						5.5'		
28-11	2209	1218-1226	4224'	283.6	VERY GOOD	4.5'	VERY GOOD	400
28-12						4.5'		
28-13	2209	1226-1233	3696'	105.6	VERY GOOD	5.0'	VERY GOOD	400
28-14						5.0'		

*deg/half-mile

**vehicles per day

TABLE 2 ALIGNMENT DATA FOR INVESTIGATED CURVED SECTIONS

SOURCE OF FUND: NATIONAL SCIENCE FOUNDATION LANE WIDTH: 11 FEET

SECTION NUMBER	COUNTY NUMBER	REFERENCE MARKERS	DEGREE OF CURVE	LENGTH OF CURVE	SUPER-ELEVATION	GRADIENT	SIGHT DISTANCE	TRAFFIC WARNING DEVICES
1	2	3	4	5	6	7	8	9
3-21	7504	1497-1504	5.0°	350'	2.0%	-4.0%	0.2 mi.	55 mph
3-22						-4.0%	0.2 mi.	
3-23	7504	1506-1510	5.7°	1200'	4.0%	+2.0%	0.1 mi.	50 mph
3-24						+2.0%	0.1 mi.	
13-1	3204	3075-3080	4.0°	1056'	3.0%	0.0%	0.2 mi.	ARROW
13-2						0.0%	0.2 mi.	
13-3	3204	3093-3104	37.0°	528'	5.5%	0.0%	0.2 mi.	20 mph
13-4						0.0%	0.2 mi.	CHEV.
13-5	3204	3101-3111	5.8°	528'	4.0%	-2.0%	0.2 mi.	CHEV.
13-6						+2.0%	0.2 mi.	
14-1	3705	1043-1051	13.4°	650'	4.5%	0.0%	0.2 mi.	30 mph
14-2						0.0%	0.2 mi.	CHEV.
14-3			10.4°	625'	3.5%	-1.0%	0.2 mi.	30 mph
14-4						+1.0%	0.2 mi.	CHEV.
19-3	4103	1142-1156	10.4°	700'	5.5%	-1.0%	0.1 mi.	35 mph
19-4						+1.0%	0.1 mi.	
19-5	4602	1262-1273	15.2°	775'	7.0%	0.0%	0.1 mi.	25 mph
19-6						0.0%	0.1 mi.	CHEV.
28-9	2209	1006-1014	5.5°	1584'	4.5%	-2.0%	0.2 mi.	45 mph
28-10						+2.0%	0.2 mi.	
28-11	2209	1218-1226	10.7°	650'	5.5%	-1.0%	0.1 mi.	35 mph
28-12						-1.0%	0.1 mi.	CHEV.
28-13	2209	1226-1233	4.0°	300'	2.0%	-2.5%	0.1 mi.	NONE
28-14						+2.5%	0.1 mi.	

TABLE 3 SPEED DATA

SOURCE OF FUND: NATIONAL SCIENCE FOUNDATION					LANE WIDTH: 11 FEET
SECTION NUMBER	NUMBER OF PASSENGER CARS	AVERAGE SPEED (MPH)	85% SPEED (MPH)	STANDARD DEVIATION (MPH)	ERROR (MPH)
1	2	3	4	5	6
3-21	62	51.2	56.3	6.0	1.5
3-22	47	51.8	56.0	4.9	1.4
3-23	31	48.3	51.1	4.5	1.6
3-24	39	48.6	52.9	4.5	1.4
13-1	40	53.9	56.8	4.2	1.3
13-2	36	54.9	57.9	4.6	1.5
13-3	39	26.5	28.4	4.5	1.4
13-4	51	25.9	28.2	4.7	1.3
13-5	84	54.9	57.8	7.0	1.5
13-6	92	53.1	56.3	5.9	1.2
14-1	50	41.7	44.7	5.1	1.4
14-2	50	43.2	44.3	4.7	1.3
14-3	50	42.2	45.8	4.7	1.3
14-4	62	42.3	45.6	5.6	1.4
19-3	66	44.5	47.1	5.0	1.2
19-4	75	44.6	46.4	4.9	1.1
19-5	71	39.3	40.8	3.5	0.8
19-6	52	36.7	39.3	5.5	1.5
28-9	81	46.7	50.5	6.0	1.3
28-10	71	46.7	50.7	5.2	1.2
28-11	64	43.2	46.0	5.7	1.4
28-12	55	42.0	44.5	4.2	1.1
28-13	71	50.1	53.5	6.4	1.5
28-14	81	47.9	52.3	5.5	1.2

1. Degrees of curve obtained from the design plans found in NYSDOT regional offices.
2. Length of section and length of curve (ft), measured in the field.
3. Superelevation rate (percent), measured in the curve using an inclinometer and later compared with the superelevation rate on the design plans in NYSDOT regional offices as a control, wherever possible.
4. Gradient (percent), measured in the field using an inclinometer and later compared with the gradient on the design plans in NYSDOT regional offices as a control, where possible.
5. Sight distance (mi), roughly estimated in the field for each direction of traffic to specific curves of interest.
6. Lane width (ft), measured in the field.
7. Shoulder width (ft), measured in the field.
8. Average annual daily traffic (veh/day), obtained by using the most recent NYSDOT Traffic Volume Report.
9. Traffic warning devices, if present, and their locations as measured by mile markers were recorded for each direction of traffic. Included were arrow signs, advisory speed plates (recommended speeds), and chevrons.
10. Speed data (mph), 85th percentile speed, average speed in curves and tangents for passenger cars, pickups and vans, and trucks under free flow conditions. It is estimated that about 61,000 speeds of vehicles under free flow conditions were collected. The speed data were collected during off-peak periods to negate the influence that time of day might have on operating speeds.
11. Accident data for the 261 curved sites under study, consisting of 815 accidents from January 1981 to December 1984 were obtained for all vehicle types from the New York State Accident Surveillance System's (SASS) accident description file.

Descriptive information for these data exists for all of the investigated 261 road sections, as well as for the corresponding horizontal curves within the sections. The data collection and

TABLE 4 ACCIDENT DATA FOR INVESTIGATED CURVED SECTIONS

SOURCE OF FUND: NATIONAL SCIENCE FOUNDATION																				LANE WIDTH: 11 FEET		
	WEATHER CONDITION					ROAD CONDITION				LIGHT CONDITION					ACCIDENT SEVERITY				ACCIDENT TYPE			
SECTION NUMBER	CLEAR	CLOUD	RAIN	SNOW	OTHER	DRY	WET	ICE	OTHER	DAYLIT	DUSK	DAWN	DARK	OTHER	FATAL	INJURY	P.D.O.	OTHER	MULTI.	SINGLE	OTHER	TOTAL
1	2					3				4					5				6			7
3-21,22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-23,24	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	1	1
13-1,2	0	0	1	0	2	0	1	0	2	0	0	0	1	2	0	1	0	2	0	1	2	3
13-3,4	1	1	1	0	4	2	1	0	4	2	0	0	1	4	0	2	1	4	1	2	4	7
13-5,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14-1,2	1	1	1	1	3	1	2	1	3	3	0	0	1	3	0	4	0	3	1	3	3	7
14-3,4	1	1	0	0	2	1	1	0	2	1	0	0	1	2	0	2	0	2	0	2	2	4
19-3,4	2	1	0	0	2	2	0	1	2	1	0	1	1	2	0	3	0	2	1	2	2	5
19-5,6	1	3	0	1	1	3	1	1	1	1	0	0	3	1	0	2	2	1	2	2	1	5
28-9,10	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	1	1
28-11,12	0	0	2	0	1	0	2	0	1	1	0	0	1	1	0	2	0	1	0	2	1	3
28-13,14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

reduction process encompasses field and office work from June 1984 to May 1986.

Cross classification information for the range of volumes and degrees of curve (*DC*) for lane widths of 10, 11, and 12 ft is given in the following two tables.

Lane Width (ft)	Degree of Curve (DC, per 100 ft)				
	0°	1°–5°	>5°–10°	>10°	Total
10	6	8	39	32	85
11	8	26	38	20	92
12	12	50	14	8	84
Total	26	84	91	60	261

Lane Width (ft)	Volume (vpd)				
	<1,000	1,000–2,000	2,000–3,000	>3,000	Total
10	37	26	18	4	85
11	27	57	4	4	92
12	5	19	30	30	84
Total	69	102	52	38	261

RELATIONSHIP BETWEEN CURVATURE CHANGE RATE AND OPERATING SPEED

Extensive investigations *(11, 17–20)* have shown that speed characteristics on horizontal alignments can be adequately described in terms of the curvature change rate design parameter *CCR*, defined as the absolute sum of the angular changes per section length of roadway with similar road characteristics. A section is any length of horizontal alignment that exhibits similarity in road characteristics, such as similar radii of curves or similar cross sections. *CCR* (degrees/half-mile) is expressed in the following way:

$$CCR = \left(\sum_i \left| \frac{L_i}{R_i} \right| + \sum_j \left| \frac{L_j}{2R_i} \right| \right) (57.3)\ (2{,}640)/L \qquad (1)$$

where

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

Calculated values for *CCR* can be found in Table 1.

Regression analysis was used to determine the relationship between *CCR* and operating speed. The resulting regression equations for passenger cars, by lane widths, are as follows:

Lane width 10 ft:

$$\hat{V}85 = 55.132 - 0.042\ (CCR) \qquad (2)$$

$R^2 = 0.846$
$SEE = 2.753$ mph

Lane width 11 ft:

$$\hat{V}85 = 57.602 - 0.040\ (CCR) \qquad (3)$$

$R^2 = 0.731$
$SEE = 2.721$ mph

Lane width 12 ft:

$$\hat{V}85 = 59.515 - 0.038(CCR) \qquad (4)$$

$R^2 = 0.836$
$SEE = 2.261$ mph

where

$\hat{V}85$ = estimate of 85th percentile speed (mph),
CCR = curvature change rate (degrees per half-mile),
R^2 = coefficient of determination, and
SEE = standard error of estimate.

As can be seen, there is a strong correlation between 85th percentile speed and *CCR* for all lane widths as implied by the large coefficient of determination R^2. From these equations, contrary to the curvilinear relationships found in Germany *(17, 19)*, the driving behavior in New York State related to *CCR* is described by linear relationships. For the second-order term of a curvilinear regression equation, the *t*-test yielded nonsignificant results at the 95 percent level of confidence for all lane widths.

The linear regression equations are plotted in Figure 1, which shows the relationship between operating speed and *CCR* for different lane widths.

The potential usefulness of the graph is obvious. By knowing the lane width and difference in *CCR* between two road sections with similarities in horizontal alignment the expected change in operating speed between the two sections can be predicted. For example, if a roadway with lanes 10 ft wide has a tangent section with *CCR* = 0 followed by a curved section with *CCR* = 400 degrees per half-mile, the expected changed in operating speed is approximately 55 – 39 = 16 mph. Furthermore, for an observed road section, differences between the selected design speed and the expected operating speed can be predicted in the early design or redesign stages.

In order to use the curvature change rate procedure, it must be clear as to what is meant by homogeneous sections, or similarity in road characteristics. While such a section can be defined as having similar design elements for the horizontal alignment, it still can be difficult to comprehend this concept. Graphical techniques were developed to identify subsections with similarities in horizontal alignment *(17, 19)* to alleviate this problem.

For typical old alignments, for example, in the case of RRR projects, it is usually more difficult to find road sections of appreciable lengths with similarities in horizontal alignment than for newer more curvilinear ones. In these cases, dividing the road into uniform subsections results mainly in analyzing each curve individually. For single curves, the curvature change rate formula reduces to just the degree of curve.

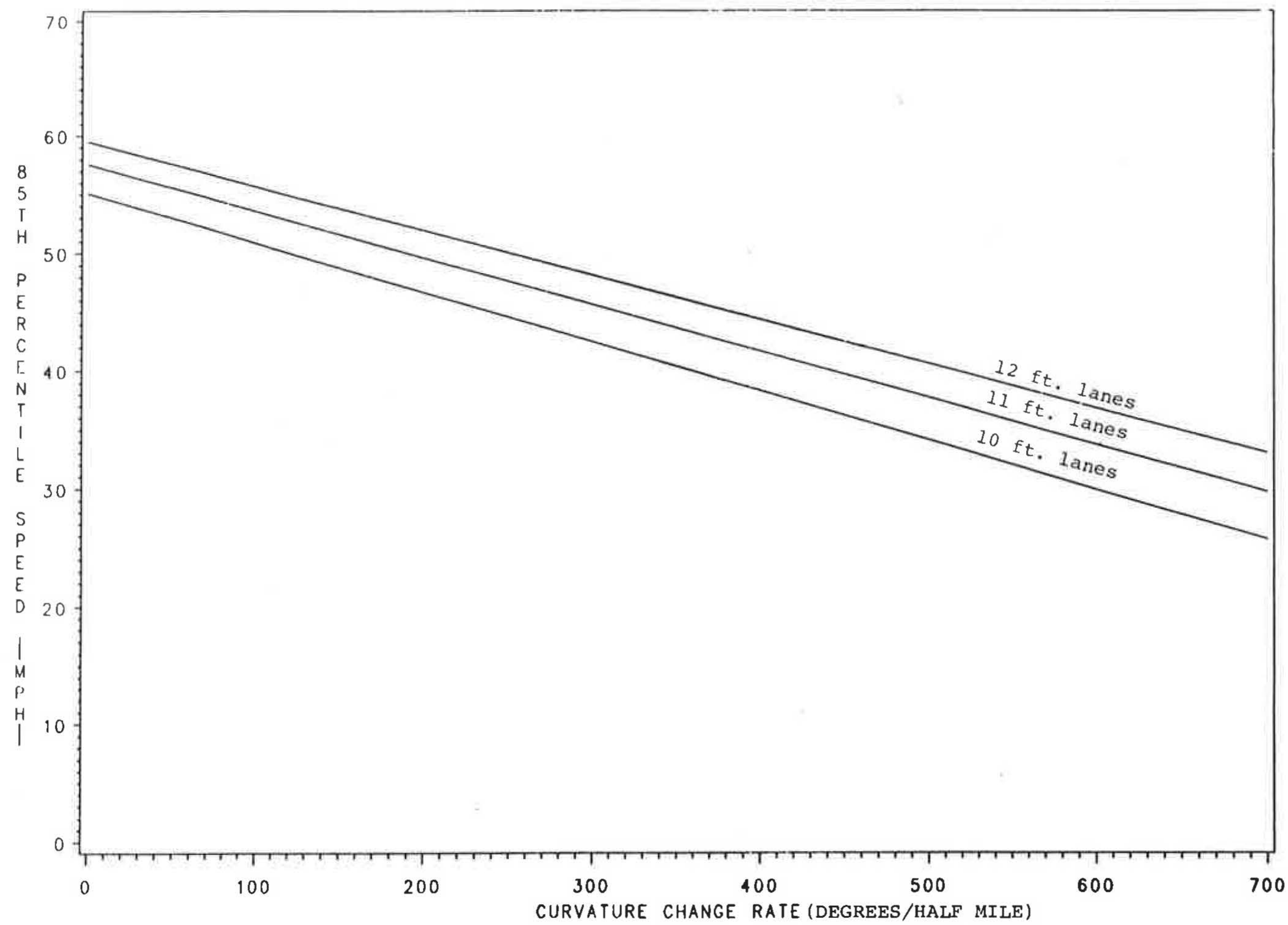

FIGURE 1 Relationship between 85th percentile speed and curvature change rate (*CCR*) for passenger cars.

RELATIONSHIP BETWEEN DEGREE OF CURVE AND OPERATING SPEED

Regression analysis was also used to determine the relationship between degree of curve (*DC*) and 85th percentile speed. For passenger cars, the regression equations are as follows:

Lane width 10 ft:

$$\hat{V}85 = 55.646 - 1.019(DC) \quad (5)$$

$R^2 = 0.753$
$SEE = 3.485$ mph

Lane width 11 ft:

$$\hat{V}85 = 58.310 - 1.052(DC) \quad (6)$$

$R^2 = 0.746$
$SEE = 2.646$ mph

Lane width 12 ft:

$$\hat{V}85 = 59.746 - 0.998(DC) \quad (7)$$

$R^2 = 0.824$
$SEE = 2.344$ mph

where *DC* is measured in degrees (°) per 100 ft.

A plot relating 85th percentile speed to *DC* is shown in Figure 2. By knowing the change in *DC* between two successive curves or between a curve and a tangent, the expected changes in operating speed can be predicted in the same way as with *CCR*. Again, the *t*-test showed nonsignificant results at the 95 percent level of confidence for all lane widths for the second-order term of a curvilinear regression equation.

Comparison of design parameters *CCR* and *DC* related to operating speeds shows that similarly valid results can be achieved in the United States by using *DC*. For the present database, Figures 1 and 2 show that estimates of the 85th percentile speed can be achieved by applying either of these design parameters without committing significant error when related to single curves or curved sections.

Because the American design, especially for two-lane rural roads, mainly consists of sequences of tangents and curves (or curved sections), the parameter *DC* will be used for future recommendations to detect critical operating speed changes in horizontal alignment. In the case of curvilinear alignments, the *CCR* method may have an advantage over the *DC* method.

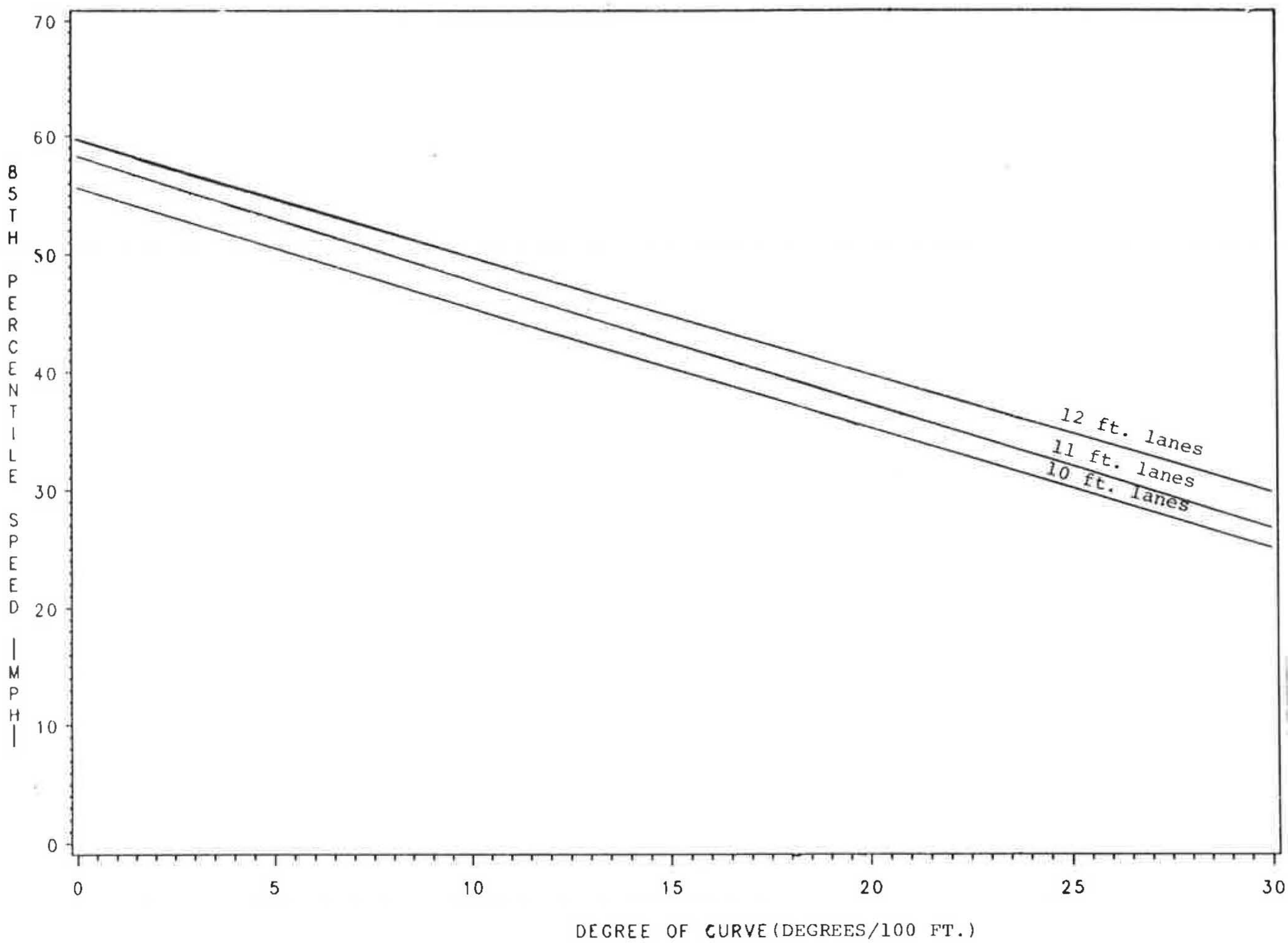

FIGURE 2 Relationship between 85th percentile speed and degree of curve (*DC*) for passenger cars.

EXAMPLE APPLICATIONS FOR BOTH METHODS

To determine the change in operating speed by using the previously discussed methods. Figure 3 shows a typical road section consisting of a curve and two long tangents located on State Route 19, Section Number 19–5/6, in open country in New York State (Tables 1–4). The pavement width is 22 ft, lane width 11 ft, with additional shoulders of 3 ft on both sides. Pavement conditions were good, whereas shoulder conditions were fair. On the approaches to the curve from both sides, advisory speed plates of 25 mph combined with arrow sign designations were installed. In addition, the curved section was equipped with chevrons.

By applying Figure 1 for *CCR*, one obtains the following expected operating speeds for an 11-ft lane:

Tangent: $CCR = 0$, $\hat{V}85 = 58$ mph
Curve: $CCR = 401$ degrees per half-mile, $\hat{V}85 = 42$ mph
Speed change: $\Delta\hat{V}85 = 16$ mph

By applying Figure 2 for *DC*, one obtains the following expected operating speeds for an 11-ft lane:

Tangent: $DC = 0°$, $\hat{V}85 = 58.5$ mph
Curve: $DC = 15.2°$, $\hat{V}85 = 42.5$ mph
Speed change: $\Delta\hat{V}85 = 16$ mph.

The observed 85th percentile speed for both directions on the curve (from Table 3) was $V85 \cong 40$ mph; the observed 85th percentile speed for both directions on the tangent was $V85 \cong 57.5$ mph; and the resulting observed speed change was $\Delta V85 = 17.5$ mph. Thus, for the example application, two conclusions could be drawn:

1. Actually measured 85th percentile speeds agree well with the expected operating speeds of Figures 1 and 2 for the tangents and curve.
2. The *DC* method leads to the same results as the *CCR* method.

It is interesting to note that in spite of the applied stringent traffic warning devices, the expected change in the speed profile is still 16 mph based on Figures 1 and 2, which agrees well with the actually measured change of 17.5 mph. These speed changes are far larger than the maximum allowable speed changes suggested by Leisch's method *(7)* of 10 mph, by the Swiss standard *(12)*, and by the German design guidelines *(17)*, indicating that a severe inconsistency in horizontal alignment exists that could lead to critical driving maneuvers.

Figure 3 shows a typical example taken from the 261 investigated road sections; more serious conditions could easily have been selected.

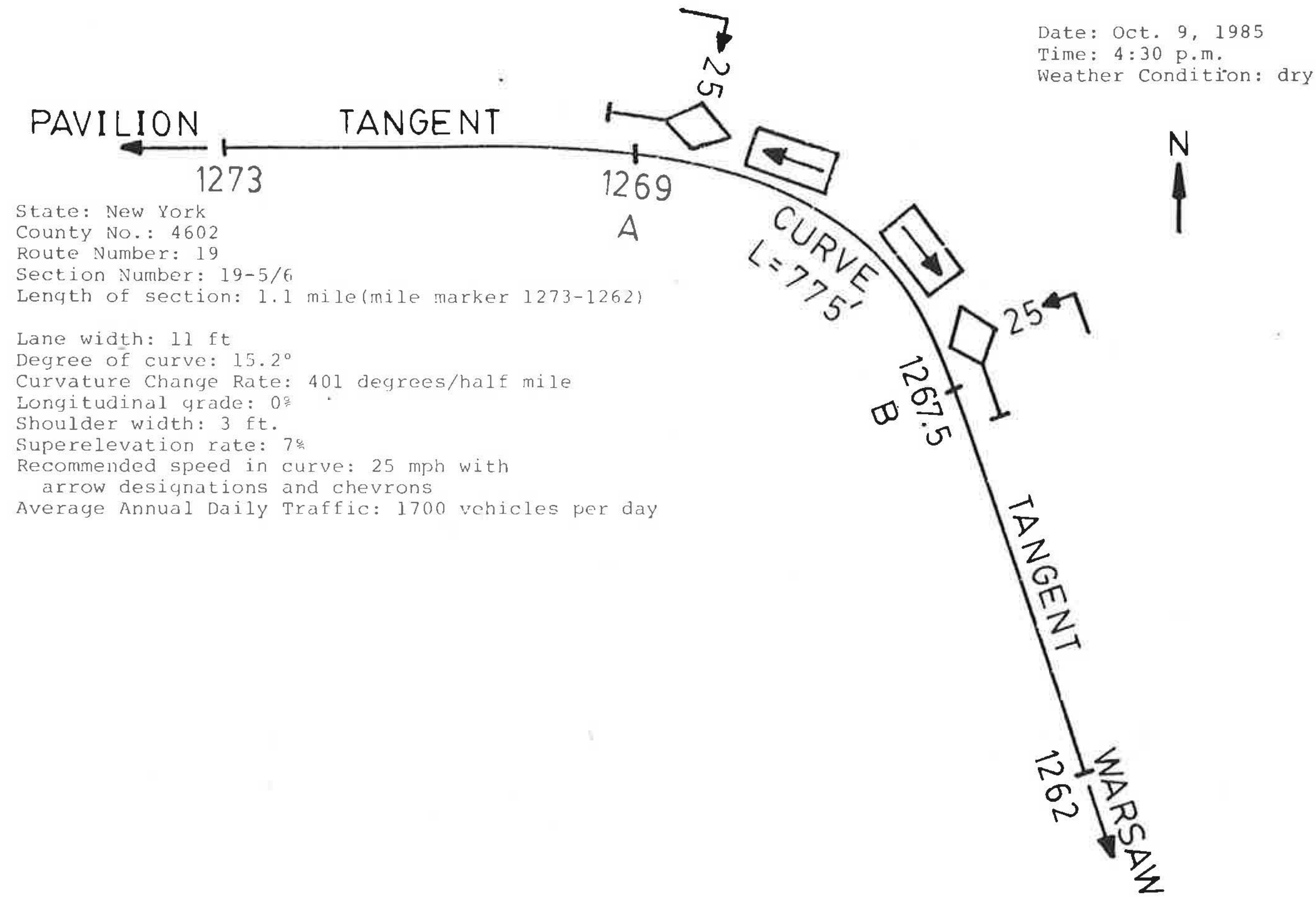

FIGURE 3 Information about an investigated road section on State Route 19 in northern New York State.

EFFECT OF OTHER PARAMETERS ON OPERATING SPEEDS

There are many factors that affect operating speeds. A detailed discussion of these factors is given by Lamm *(3)* and by Choueiri *(21)*. To give a more detailed evaluation of the relationship among design parameters, volume, and operating speed, factors consisting of degree of curve, lane width, length of curve, shoulder width, superelevation rate, sight distance, gradient, recommended speed, and average annual daily traffic must be taken into consideration.

Use was made of two statistical methods, the analysis of variance test and the regression analysis. The analysis of variance was used to determine whether or not particular variable produce significant effects on vehicular speed. Regression analysis was used to obtain quantitative estimates of the effects produced.

In particular, for the evaluation of the quantitative effects of these factors, the multiple linear stepwise regression technique was used. The stepwise technique consists of adding one independent variable to the regression equation in each step. Thus, the stepwise process produces a series of multiple regression equations, in which each equation has one independent variable more that its predecessor in the series. The following stipulations were used to terminate the stepwise process and to determine the final multiple regression equation:

1. The selected equation has to have a multiple regression coefficient R^2 that is significant at the 0.05 level.
2. Each of the independent variables included in the multiple regression equation has to have a regression coefficient that is significantly different from zero at the 0.05 level.

The selected multiple regression equation had to fulfill both stipulations.

Other conditions assumed to hold were as follows:

1. *DC* was taken as positive whether a curve turned left or right because there was no significant effect on speed, proved statistically at the 0.05 level, from a curve bearing left as opposed to a curve turning right.
2. An uphill gradient was treated as positive, whereas a downhill gradient was treated as negative.
3. Because *DC* and recommended speed were highly correlated, it was decided not to include both of them in the same regression equation.
4. When no advisory speed signs (recommended speeds) were posted in curves, the nationwide speed limit of 55 mph was taken into consideration.

Based on these stipulations, the following equation was obtained for the operating speed of passenger cars:

$$\hat{V}85 = 34.700 - 1.00(DC) + 2.081(LW) + 0.174(SW) + 0.0004(AADT) \quad (8a)$$

$R^2 = 0.842$
$SEE = 2.814$ mph

where

$\hat{V}85$ = estimate of the operating speed expressed by the 85th percentile speed (mph),
DC = degree of curve (range 0° to 27°),
LW = lane width (ft),
SW = shoulder width (ft),
$AADT$ = average annual daily traffic (vpd),
R^2 = coefficient of determination, and
SEE = standard error of estimate (mph).

The independent variables in Equation 8a were selected by the stepwise regression technique in the order *DC, LW, AADT,* and *SW*. For instance, *DC* had the highest correlation with the dependent variable $\hat{V}85$, and thus it was the first variable to be included in Equation 8a, and so forth.

As can be seen from Equation 8a, the design parameters sight distance, length of curve, and gradient (up to 5 percent) were not included in the model because the regression coefficients associated with these parameters were not significantly different from zero at the 95 percent confidence level. Superelevation rate *SE* was not included in the predictive regression equation because it was highly correlated with *DC* (R = 0.801).

However, comparing Equation 8a with the following equation, which includes only the design parameter *DC*, shows that the effect of *LW, SW,* and *AADT* amounts to only about 5.5 percent of the variation in the estimated operating speeds.

$$\hat{V}85 = 58.656 - 1.135(DC) \qquad (8b)$$

$R^2 = 0.787$
$SEE = 3.259$ mph

This small standard error (3.259 mph) and moderately large R^2 value (0.787) suggest that the relationship represented by Equation 8b is a strong competitor to that represented by Equation 8a.

By introducing design and volume data of the investigated road section in Figure 3 into Equations 8a and 8b, the following results were obtained:

Tangent:

$\hat{V}85 \cong 59.0$ mph (from Equation 8a)
$\hat{V}85 \cong 58.5$ mph (from Equation 8b)

Curve:

$\hat{V}85 \cong 43.5$ mph (from Equation 8a)
$\hat{V}85 \cong 41.5$ mph (from Equation 8b)

Speed change:

$\Delta\hat{V}85 = 15.5$ to 17 mph

These results compare well with each other and with those found by applying Figure 2. The same agreement holds for the expected change in the operating speed between the tangents and the curved sections, confirming once again the reliability of the relationship developed between *DC* and operating speed in Figure 2. The influence of advisory speed signs on operating speed, the following equation was obtained for passenger cars *(3, 21)*:

$$\hat{V}85 = 25.314 + 0.554(RS) \qquad (9)$$

$R^2 = 0.719$
$SEE = 3.743$ mph

where *RS* equals recommended speed (mph).

This small standard error (3.743 mph) and large R^2 value (0.719) suggest that the relationship represented by Equation 9 is a strong one.

Equation 9 was introduced only to show the effect of advisory speed signs on operating speeds for two-lane rural highways. Because the main objective of this paper was to study consistency in horizontal alignment, no further analysis of the effect of advisory speed signs on the driving behavior is given.

RECOMMENDATIONS FOR DETECTING INCONSISTENCIES IN HORIZONTAL ALIGNMENT

Up to now, only the recommendations of Leisch *(7)*, the German design guidelines *(17)*, and the Swiss standard *(12)* about favorable sequences of horizontal design elements that avoid critical inconsistencies in operating speeds have existed. All three procedures agree that by limiting changes in operating speed between road sections to certain ranges, it can be determined whether the break in the speed profile is acceptable, or may cause a speed change that could lead to critical driving maneuvers. The maximum allowable speed change is between 6 mph (German design guidelines) and 12 mph (Swiss standard). From Equation 8b, a speed change of 6 mph corresponds to a change in *DC* of about 5°, and a speed change of 12 mph corresponds to a change in *DC* of about 10.5°, between successive design elements, for example, between a tangent and a curve. Thus, the following assumptions may express the current state of the art for reasonable changes in degree of curve and operating speed:

- Good designs may exist up to changes of

  $\Delta DC \leq 5°$
  $\Delta V85 \leq 6$ mph (10 km/hr)

- Poor designs may exist for changes of

  $\Delta DC > 10°$
  $\Delta V85 > 12$ mph (20 km/hr)

These changes gain support from the study of 261 selected road sections on which some related research studies *(3, 21)* are based. It was found that tangent-to-curve transitions in the range of $\Delta DC \leq 5°$ in about 90 percent of all cases were unequipped with any kind of advisory speed sign, and only rarely with arrow designations. Curves or curved sections, which fall into the range 5° to 10°, were normally equipped with recommended speeds ranging from 35 to 50 mph, often combined with arrow designations. Curves beyond 10° were mostly equipped with recommended speeds ranging from 15 to 35 mph, combined with arrow signs and, in many cases, with chevrons. These differences could be attributable to the fact that the highway engineer recognized by his experience or by past accident histories the danger behind transitions for which changes in *DC* exceeded a certain margin, assumed from this study to be about $\Delta DC > 10°$.

In this connection, preliminary studies based on previous research *(3, 21)* were conducted on a total of 815 accidents from January 1981 to December 1984 to determine the relationship between accident rate and *DC*. The accident data were only related to the curves or curved sections within the observed 261 roadway sections.

By using regression analysis, the following linear equation for all lane widths and vehicle types gave a quantitative estimate of the effect produced by *DC* on accident rate.

$$\widehat{ACCR} = (-0.880) + (1.410)DC \quad (1° \leq DC \leq 27°) \qquad (10)$$

$R^2 = 0.434$
$SEE = 8.525$ accidents per million vehicle-miles

where $\widehat{ACCR}$ is the estimate of the accident rate in accidents per million vehicle-miles (acc/mvm).

The relatively small coefficient of determination (0.434) and the relatively large standard error (8.525 acc/mvm) in Equation 10 are not at all surprising because accident research relationships are not simple and direct ones, but are often complex, and changes in frequency of accidents are often the result of many factors in addition to the design parameters and traffic volume data.

From Equation 10, for 5° of curve an accident rate of about 6 acc/mvm and for 10° of curve an accident rate of about 13 acc/mvm are expected for the present database. Thus, the accident risk on sections with $\Delta DC > 10°$, as compared with that on sections with $\Delta DC \leq 5°$, is about 2.0 times larger for the case of unfavorable transitions between successive design elements, for example, between a tangent and a curve. These findings support once more the recommendation that the maximum allowable change in *DC* should be 10°.

However, the small coefficient of determination (0.434) of Equation 10 suggests that caution should be exercised when interpreting these results.

PROCESS FOR EVALUATING HORIZONTAL DESIGN CONSISTENCY

Primarily at smaller design speeds, the changing alignment causes variations in operating speeds. These variations mean that the horizontal curves that control the design speed along the highway cause the driver first to increase speed on the flatter portions of the alignment and then to decrease speed on the sharper or controlling curves *(7)*, increasing the accident risk by a substantial amount. Therefore, one of the important tasks in modern rehabilitation of the two-lane rural network in the United States is to ensure design consistency and to detect critical inconsistencies in horizontal alignment, especially with regard to RRR projects.

To achieve these goals, the following design process is recommended:

1. Assess the road section where new design or redesign projects shall be conducted. For example, see Figure 3 from mile marker 1262 to mile marker 1273.
2. For this road section, determine the *DC* for each design element. For the tangent, $DC = 0°$; for the curve, $DC = 15.2°$.
3. Determine the expected operating speed for each design element by applying the nomographs for the relationship between *DC* and 85th percentile speed from Figure 2, depending on the lane width of the section. For the tangent, $\hat{V}85 = 58.5$ mph; for the curve, $\hat{V}85 = 42.5$ mph.
4. For every two successive design elements (only in the direction of increasing *DC*, the change in the degree of curve (ΔDC) and the corresponding change in the operating speed ($\Delta\hat{V}85$) could be calculated. $\Delta DC = 15.2°$, $\Delta\hat{V}85 = 16$ mph.
5. Determine all road sections where changes in *DC* and changes in operating speed correspond to $\Delta DC < 10°$ and $\Delta V85 < 12$ mph. These road sections represent consistency in horizontal alignment, or at least minor inconsistencies. Normally, for changes in *DC* of up to 5° the horizontal alignment can be evaluated as good design. Changes in degrees of curve between 5° and 10° (fair design) would warrant traffic warning devices but not redesigns unless there was a documented safety problem.
6. Determine all road sections where changes in *DC* exceed 10° per 100 ft and changes in operating speed exceed 12 mph. For these road sections, major geometric defects in horizontal alignment exist. Normally, for example, in case of RRR projects, redesigns of at least hazardous road sections are recommended. Thus, $\Delta DC = 15.2°$ and $\Delta V85 = 16$ mph are conditions in need of redesign.

Strong inconsistencies in the horizontal geometric design have been revealed, especially in transitions between the tangents and the curve. For example, critical speed changes occur before point A at mile marker 1269 for west-east travel, and before point B at mile marker 1267.5 for southeast-northwest travel.

However, before a definite decision is made, for example, about a redesign, the accident situation on the given road section should be additionally checked. For the example application in Figure 3, an accident rate of 18.3 acc/mvm was evaluated. This accident rate exceeded by far the expected common accident rates for good or even fair designs. The considerations related to changes in *DC* and operating speed and to the accident rate on the given road section in Figure 3 appear to indicate that some kind of redesign is worth noting for this case, because here even stringent traffic warning devices were not effective in correcting dissimilarities in the horizontal alignment.

By applying this process, the highway engineer could control consistencies and minor inconsistencies in highway alignment and detect and correct major geometric defects, for example, in conducting RRR projects.

CONCLUSION

Based on the current research *(3)*, the results appear to indicate that

- Good designs seem to exist for *DC* changes of up to 5° between successive design elements. For these road sections, consistency in horizontal alignment exists and the horizontal alignment is correct. For example, RRR-type improvements can be installed in most cases without considering traffic warning devices or even horizontal redesigns. New designs should normally not exceed changes in *DC* of more than 5° per 100 ft. The majority of existing state routes in the United States correspond to horizontal alignments of this magnitude.
- Fair designs appear to exist for *DC* changes between 5° and 10° between successive design elements. These road sections may represent at least minor inconsistencies in geometric

design. Normally, they would warrant traffic warning devices but no redesigns unless there was a documented safety problem as numerous experiences in the United States *(22–24)* and in Europe *(17, 25–27)* have shown. To achieve a high level of driving dynamic safety, superelevation rates and stopping sight distances should be related to the expected operating speeds, wherever possible.

- Poor designs seem to exist for *DC* changes of more than 10° between successive design elements. These road sections may represent strong inconsistencies in horizontal geometric design combined with those breaks in the speed profile that may lead to critical driving maneuvers. Normally, for example, for RRR projects, redesigns of at least hazardous road sections are recommended. But, before any definite decision is made, the expected accident situation on the given road section should be checked.

Finally, in continuation of the research of Lamm *(3)*, current trends are focusing on statistical analysis techniques of a larger sample of accidents to further quantify the suggested *DC* changes and operating speed for good, fair, and poor designs. Another main objective will be to determine if the results found for two-lane rural state routes in the state of New York differ significantly from other geographical areas in the United States or can be made transferable.

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REFERENCES

1. J. Hayward, R. Lamm, and A. Lyng. *Survey of Current Geometric and Pavement Design Practices in Europe: Geometric Design.* International Road Federation, July 1985.
2. *A Policy on Geometric Design of Highways and Streets.* AASHTO, Washington, D.C., 1984.
3. R. Lamm. *A Design Procedure to Determine Critical Dissimilarities in Horizontal Alignment and Enhance Traffic Safety by Appropriate Low-Cost or High-Cost Projects.* Final Report, Grant ECE-8414755, National Science Foundation, March 1987.
4. *A Policy on Highway Types (Geometric).* Special Committee on Design Policies. AASHO, Washington, D.C., 1940.
5. *A Policy on the Geometric Design of Rural Highways.* AASHO, Washington, D.C., 1954.
6. *A Policy on the Geometric Design of Rural Highways.* AASHO, Washington, D.C., 1965.
7. J. E. Leisch and J. P. Leisch. New Concepts in Design Speed Application. In *Transportation Research Record 631.* TRB, National Research Council, Washington, D.C., 1977, pp. 4–14.
8. R. Lamm. *Driving Dynamics and Design under Special Consideration of Operating Speeds.* Publications of the Institute of Highway and Railroad Design and Construction, University of Karlsruhe, Vol. 11, Federal Republic of Germany, 1973.
9. J C. Hayward. Highway Alignment and Superelevation: Some Design-Speed Misconceptions. In *Transportation Research Record 757.* TRB, National Research Council, Washington, D.C., 1980.
10. G. Koeppel and H. Bock. Operating Speed as a Function of Curvature Change Rate. *Road Construction and Road Traffic-Technique,* Vol. 269, Federal Republic of Germany, 1979.
11. *Geometric Design Standards. Guidelines for the Design of Rural Roads.* RAL-L-1. German Road and Transportation Research Association, Committee 2.3, 1973.
12. *Highway Design, Fundamentals, Speed as a Design Element.* SN 640080a. Swiss Association of Road Specialists (VSS), 1981.
13. *Instruction sur les conditions techniques d'aménagement de routes nationales.* Ministère de l'Equipement et du Logement, France, 1975.
14. *Highway Link Design, Geometric Alignment Standards.* Departmental Standard TD9/81. Department of Transport, Great Britain, 1981.
15. *Standard Specifications for Geometric Design of Rural Roads.* National Swedish Road Administration, Sweden, 1982.
16. *Geometric Design Standards. Commentary to the Guidelines for the Design of Rural Roads.* RAL-L-1. German Road and Transportation Research Association, Committee 2.3, 1979.
17. *Geometric Design Standards. Guidelines for the Design of Roads.* RAS-L-1. German Road and Transportation Research Association, Committee 2.3, 1984.
18. R. Lamm and J. G. Cargin. Translation of the Guidelines for the Design of Roads (RAS-L-1), 1984, Federal Republic of Germany, and Highway Design, Fundamentals, Speed as a Design Element, SN 640080a, 1981, as discussed by K. Dietrich, M. Rotach, and E. Boppart, in Road Design, ETH Zuerich, Institute for Traffic Planning and Transport and Technique, FHWA, U.S. Department of Transportation, May 1985.
19. R. Lamm, J. C. Hayward, and J. G. Cargin. Comparison of Different Procedures for Evaluating Speed Consistency. In *Transportation Research Record 1100.* TRB, National Research Council, Washington, D.C., 1986, pp. 10–20.
20. J. G. Cargin. *Relationship Between Driving Behavior and Horizontal Alignment on Two-Lane Rural Highways in Upstate New York, Based on the Design Parameter Curvature Change Rate.* M.S. thesis, Department of Civil and Environmental Engineering, Clarkson University, Potsdam, N.Y., May 1985.
21. E. M. Choueiri. *Statistical Analysis of Operating Speeds and Accident Rates on Two-Lane Rural Highways.* Ph.D. dissertation, Clarkson University, Potsdam, N.Y., Jan. 1987.
22. *1983 Annual Evaluation Report, Highway Safety Improvement Program.* Traffic and Safety Division, New York State Department of Transportation, Albany, 1983.
23. J. M. Mason and H. C. Petersen. Survey of States' R-R-R Practices and Safety Considerations. In *Transportation Research Record 960.* TRB, National Research Council, Washington, D.C., 1984, pp. 20–26.
24. B. E. Jennings and M. J. Demetsky. Evaluation of Curve Delineation Signs. In *Transportation Research Record 1010.* TRB, National Research Council, Washington, D.C., 1985, pp. 53–61.
25. R. Lamm and J. H. Kloeckner. *Analysis and Evaluation of Speed Regulations.* 3rd Symposium for Urban Traffic Safety. The Hungarian Transportation Scientific Association, Budapest, Hungary, Oct. 1972, pp. 111–127.
26. H. G. Krebs, R. Lamm, J. H. Kloeckner, and H. G. Schlichter. Evaluation Criteria for Recommended Speeds on Two-Lane Rural Highways. *Research Road Construction and Traffic Technique,* Vol. 202, Federal Republic of Germany, 1976.
27. H. G. Krebs and R. Lamm. *Speed Regulations, Analysis of Driving Behavior and Accident Situation on Three State Routes in Hessen.* Report for the Minister of Economy and Technique, State Hessen, Federal Republic of Germany, 1976.

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