Comparison of Operating Speeds on Dry and Wet Pavements of Two-Lane Rural Highways

RUEDIGER LAMM, ELIAS M. CHOUEIRI, AND THEODOR MAILAENDER

The impact of design parameters and traffic volume on operating speeds of passenger cars is evaluated under free-flow conditions on 322 curved roadway sections of two-lane rural highways in New York state. The design parameters considered are degree of curve, length of curve, superelevation rate, gradient, sight distance, lane width, shoulder width, posted speed, and average annual daily traffic. For the evaluation of the quantitative effects of these factors on operating speeds, expressed herein by the 85th-percentile speeds, the multiple linear stepwise regression technique was used. The various stages of analyses revealed that degree of curve was the best available single-variable predictor of operating speeds on dry pavements. Other variables helped the regression model, but the equation did well even without them. Effect of wet pavements on 85th-percentile speeds of passenger cars were also examined. Analyses were performed using data from a total of 24 curved roadway sections. Ample evidence exists to indicate that wet pavement does not have a great effect on operating speed, and that drivers will not adjust their speeds sufficiently to accommodate inadequate wet pavement on curves in particular. Furthermore, results of the statistical analyses indicate that the relationship between operating speed and degree of curve, developed from speed data collected on dry pavements, is also valid for wet pavement conditions so long as visibility is not affected appreciably by heavy rain. It is obvious that the drivers do not recognize the fact that friction supply is significantly lower on wet pavements as compared with dry. For the implementation of the results for design purposes, recommendations for achieving consistency and detecting inconsistencies in horizontal alignment, as well as recommendations for harmonizing design speed and operating speed, as related to wet pavement conditions, were given for good, fair, and poor design practices. These tasks are important in modern highway design and redesign strategies for improving traffic safety.

Weather conditions have a tendency to modify vehicular speeds because of a reduction in visibility and a possible impairment of surface conditions. The general effect of wet pavement conditions is to lower friction supply between the tire and the roadway, with the amount of reduction depending on the presence of moisture, snow, and ice, or on the thickness of the water film covering the pavement. As the thickness of the water film increases, skid resistance decreases, and, in cases of heavy rain combined or not combined with geometric design deficiencies, hydroplaning conditions may occur (*1,2*). Geometric design deficiencies, as well as drainage and pavement design, could affect the incidence of wet-pavement accidents, especially at curved sites. For example, when consistency between successive design elements is not present, or a harmony between design speed and operating speed does not exist at a certain curved site (*3–8*), or an adequate dynamic safety of driving cannot be provided because of a reduction in friction factors caused by wet pavement conditions (*9*), critical driving conditions may occur. Other roadway sections, which may be hazardous when roadway surfaces are wet, have insufficient minimum or maximum superelevation rates, superelevation runoffs with insufficient longitudinal slopes, or sag vertical curves that do not satisfy, for example, the drainage requirements.

According to a report prepared by the National Transportation Safety Board (NTSB) (*10*), about 13.8 percent of all fatal highway accidents are fatal accidents that occurred on highway pavements that were wet. A study cited by NTSB of wet-pavement accidents that occurred on the West Virginia highway system revealed that the average rate of wet-weather accidents was 2.2 times the rate of dry-pavement accidents and that the maximum rate was 85 times the dry-pavement accident rate. Forty percent of the accidents on the West Virginia Interstate system occurred on wet pavement. The report estimated that the roads in West Virginia were not wet more than 15 percent of the time. If analyses of national and international data reflect findings similar to those cited by NTSB (*10*), then the wet-pavement problem should be of major concern worldwide and more resources should be allocated for correcting the sources of the problem.

A review of accidents in the United States and Europe (*11*) revealed that between 25 and 30 percent of all fatalities on both continents occurred on curves of two-lane rural highways. Analyses (*3,4*) of accidents on two-lane rural highways have indicated

1. Fatal or injury accidents accounted for more than 70 percent of the accidents on curves, whereas property damage accidents greater than $400 represented less than 30 percent; and
2. Wet pavement conditions contributed to nearly 50 percent of the accidents on curves even though vehicle mileage driven under these conditions is much lower than that on dry pavements.

R. Lamm, Institute of Highway and Railroad Engineering, University of Karlsruhe, D–7500 Karlsruhe 1, Kaiserstrasse 12, Federal Republic of Germany. E. Choueiri, North Country Community College, Route 1, Box 12, Potsdam, N.Y. 13676. T. Mailaender, Mailaender Ingenieur Consultant, D–7500 Karlsruhe 1, Mathystrasse 13, Federal Republic of Germany.

In summary, a high fatal or injury accident risk does exist on curves of two-lane rural roads, especially under wet pavement conditions.

Because of the lower coefficient of friction on wet pavement as compared with dry, wet conditions lead more frequently to critical driving maneuvers, or even accidents (*12–15*). In this connection, speed is an additional vital contributing factor in many wet weather accidents because the value of skid resistance decreases as vehicle speed increases (*9*). For this reason, geometric design guidelines (*2,16–20*) point out that for driving dynamic considerations in horizontal and vertical alignments, design speed and tangential and side friction values should be selected on the basis of wet pavement conditions.

On the basis of experiences gained in New York state, the effects of design parameters, traffic volume, and wet pavement conditions on operating free speeds of passenger cars on curved sections of two-lane rural highways are determined. The question whether drivers recognize that wet pavements offer less skid resistance than do dry pavements and that they must adjust their speeds sufficiently to accommodate wet pavement to maintain vehicle control particularly on curves is examined in detail.

DATA COLLECTION AND REDUCTION

Data collection was broken down into three categories: first, the selection of road sections appropriate for the study; second, the collection of as much field data as possible about the road sections; and third, the measurement of operating free speeds at each section.

Selection of Appropriate Road Sections

From spring 1984 to summer 1987, two-lane rural state route sections throughout northern New York, normally consisting of a sequence of tangent to curve (or curved section) to tangent, were investigated under dry pavement conditions. 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. Protected by guardrails when the height of the embankment exceeded 5 ft;
6. Grades less than or equal to 5 percent; and
7. Average annual daily traffic (AADT) between 400 and 5,000 veh/day.

The selection process attempted to maintain a regional distribution and at the same time retain the longest road segments. 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.

Field Data Collection

This stage involved obtaining as much data in the field as possible about the road sections and specifically about the curve or curved section within the observed road section. Information recorded were the degree of curve, length of curve, superelevation rate, gradient, lane width, shoulder width, sight distance, AADT, and posted speeds. These data were collected in the field and later compared with (or were directly obtained from) the design plans of the New York State Department of Transportation regional offices.

Speed Data Collection and Reduction

In order to ensure that the speeds measured represented the free speeds desired by the driver under a set of roadway conditions and were not affected by other traffic on the road, only the speeds of isolated vehicles with a minimum time gap of about 6 sec, or those heading a platoon of vehicles, were measured in this study. Speed measurements were made during daytime hours on weekdays under dry and, in some cases, under wet pavement conditions.

The basic method used for speed data collection involved the measurement of the time required for a vehicle to traverse a measured course laid out in the center of a curve. Additional speed measurements were often taken on preceding and succeeding tangents, or both, to the curved site. Length of the course was 150 ft. The method used for measuring time over the measured distance involved use of transverse pavement markings that were placed at each end of the course and an observer who started and stopped an electronic stop watch as a vehicle passed the markings. The observer was placed at least 15 ft from the pavement edge of the road to ensure that his presence would not influence the speeds of passing vehicles, but not too far away so as to minimize the cosine effect (*21*).

By applying this procedure, satisfactory speed data, which were occasionally substantiated by the use of radar devices, were obtained for both directions of travel. About 120 to 140 passenger cars under free-flow conditions were sampled at each site for both directions of traffic. Speed data were then used to obtain the operating speed, expressed herein by the 85th-percentile speed—that speed below which 85 percent of the vehicles travel.

METHODOLOGY

Many factors affect operating speeds on two-lane rural highways, including, but not limited to, characteristics of the site, characteristics of traffic and road users, characteristics of controls, and characteristics of variable factors (*22*).

Each of these factors can act in different and varying amounts at a given location. Therefore, the task of determining the influence of each on operating speeds becomes difficult.

Only the effect of the following parameters on operating speeds will be addressed: degree of curve, length of curve, lane width, shoulder width, superelevation rate, sight distance, gradient, posted recommended speed, and AADT.

For evaluation of the quantitative effects of design and traffic parameters, the multiple linear stepwise regression technique (Max R^2 improvement technique) was used (*4*). 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 than its predecessor in the series (*23,24*). 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; and
3. None of the independent variables included in the multiple regression equation are highly correlated with each other. The superelevation rate and posted speed are withheld from any subsequent regression analysis because they are highly correlated with degree of curve.

The selected multiple regression equation had to fulfill all three stipulations. In addition, the following conditions were assumed to hold:

1. Degree of curve was taken as positive whether a curve turned left or right;
2. An uphill gradient was treated as positive, whereas a downhill gradient was treated as negative; and
3. When no advisory speed signs (recommended speeds) were posted in curves, the nationwide speed limit of 55 mph was taken into consideration.

OUTCOME OF THE DATA ANALYSES

Relationships Between Variables

The analysis is based on data collected for 322 curved roadway sections under dry pavement conditions in New York state (*3,4*).

Various stages of regression analyses found that the most successful equation for explaining much of the variability in 85th-percentile speeds, in terms of statistical significance and overall form, is as follows:

Overall Equation

$$V85 = 34.700 - 1.005(\mathrm{DC}) + 2.081(\mathrm{LW}) + 0.174(\mathrm{SW}) + 0.0004(\mathrm{AADT}) \quad (1)$$

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

where

$V85$ = 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).

This small value of SEE (2.814 mph) and large R^2 (0.842) suggest that the relationship represented by Equation 1 is a strong one.

Design parameters, sight distance, length of curve, and gradient were not included in the regression model because the regression coefficients associated with these parameters were not significantly different from zero at the 95 percent level of confidence.

However, in comparing Equation 1 with the following reduced Equation 2, which only includes the design parameter DC, note from the coefficients of determination (R^2) that the influence of LW, SW, and AADT in Equation 1 explains only about an additional 5.5 percent of the variation in the expected operating speeds.

Reduced Equation

$$V85 = 58.656 - 1.135(\mathrm{DC}) \quad (2)$$

$R^2 = 0.787$
SEE = 3.259 mph

This small value of SEE (3.259 mph) and moderately large R^2 value (0.787) suggest that the relationship represented by Equation 2 is also strong, and can be considered a competitor to the relationship represented by Equation 1.

Comparison of Operating Speeds on Dry and Wet Pavements

From the current data base, 24 sites were selected to provide horizontal curves of various degrees. For instance, degree of curve varied from 0° to 27°. Grades were level or nearly level on the curved sites and for a considerable distance before and beyond, which minimized the effect of grades on operating speeds of vehicles for the following comparisons.

Observations on wet pavements were taken several weeks after speeds on dry pavements were collected. On all occasions, the surfaces were wet and rain was falling from a sprinkle to moderately heavy rain. On no occasion did it rain so hard as to affect visibility appreciably. Minimum sight distances of about 450 to 550 ft, which represent the limiting values of stopping sight distances for a design speed of 55 mph (*2*), had to be provided. This limitation is based on the results of research (*25*), which indicated that when sight distance is affected appreciably because of heavy rain, drivers tend to reduce their speeds. In other words, drivers reduce their speeds not so much on account of the danger created by lower skid resistance values on wet pavements, but rather because of limited sight distances.

Available sight distances in this study were determined by a member of the study team who drove through the study section at different fixed-time intervals. When passing a specified marked mile-marker, the driver had to clearly see a mile-marker located at a distance of 0.1 mi, or about 500 ft. If this was not possible because of impaired visibility caused by heavy rain, the driver had to inform the observer taking the measurements by waving a red flag to indicate "stop wet measurements," or a green flag to indicate "continue wet measurements." Markings were done by setting up reflectors at the mile-marker positions within the section under study.

The number of vehicles recorded varied considerably from site to site as the wet pavement studies were dependent on continued rain. Again, only the speeds of passenger cars under free-flow conditions, with a minimum time gap of at least 6 sec between successive vehicles, were recorded. An example of how the data were tabulated is presented in Table 1 with the number of free-moving vehicles and corresponding 85th-percentile speeds for both wet and dry pavement conditions and with respect to degree of curve and daily precipitation in inches.

Cumulative speed distribution curves were plotted for each location studied from these data. Figure 1 shows a typical example of the distribution of speeds on dry and wet pavements. The most notable feature of the speed data used is that there was more or less a little difference in the speed distributions of free-moving passenger cars on dry and wet pavements for all curved sites under study. Similar results were shown by Stohner (*26*).

The averages of operating speeds (expressed by the 85th-percentile speeds) on dry and wet pavements for the 24 curved road sections were 47.54 and 47.41 mph, respectively, for both directions of traffic. The observed decrease in 85th-percentile speeds caused by wet road surfaces is only 0.27 percent. However, these computations do not reflect any statistical significance.

Operating speeds on dry and wet pavements were additionally examined for each of the 24 test sections. Data were plotted in Figure 2 with the dry speeds on the *y*-axis and the wet speeds on the *x*-axis. For each test section, (a) if the operating speed on wet pavement was identical to the operating speed on dry pavement, the data point would fall on the hypothetical 45-degree diagonal line shown, (b) if the operating speed on wet pavement was greater than the operating speed on dry pavement, the data point would fall below the line, and (c) if the operating speed on dry pavement was greater than the operating speed on wet pavement, the data point would be above the line. As shown in Figure 2, the data are random with points distributed both above and below the hypothetical 45-degree line.

In order to determine whether or not operating speeds on dry pavements were significantly different from operating speeds

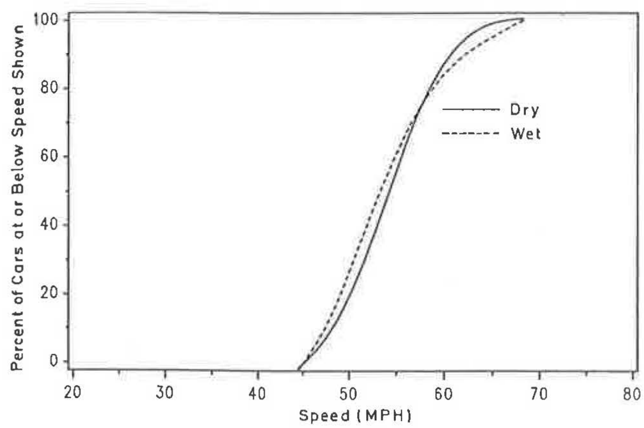

FIGURE 1 Typical example illustrating the distribution of speeds on dry and wet pavements on SR 3, county 7302, between Mile Markers 3187 and 3193.

TABLE 1 EXAMPLE FOR ALIGNMENT DATA AND OPERATING SPEEDS ON DRY AND WET PAVEMENTS (NEW YORK STATE)

ROUTE NUMBER	SPOT OF SPEED MEASUREMENT				OPERATING SPEEDS ON DRY PAVEMENTS		OPERATING SPEEDS ON WET PAVEMENTS		
	MILE-MARKER	COUNTY NUMBER	DEGREE OF CURVE	SUPER-ELEVATION	NO. OF CARS	85 % SPEED	NO. OF CARS	PRECIPI-TATION	85 % SPEED
			DEG./100 FT	PERCENT		MPH		INCHES	MPH
3	3187-	7302	2.5	2.0	57	59.3	43	0.08	59.9
	3193		2.5	2.0	54	59.4	58	0.08	58.6
3	3245-	7302	5.0	3.0	62	57.4	44	0.01	58.5
	3248		5.0	3.0	56	58.3	50	0.01	58.2
11B	1069-	7501	3.5	2.5	60	59.2	44	0.11	59.1
	1073		3.5	2.5	73	57.2	48	0.11	56.0
37	1076-	7301	0.0	--	56	59.7	54	0.04	56.5
	1082		0.0	--	65	55.5	50	0.04	57.2
37	1541-	7502	1.0	1.5	55	58.0	52	0.08	56.0
	1546		1.0	1.5	55	56.0	55	0.08	56.6
37	1152-	7203	2.3	1.5	52	52.3	52	0.04	50.6
	1156		2.3	1.5	71	48.5	62	0.04	53.3
37	1053-	7502	3.0	2.5	66	56.9	53	0.08	56.1
	1056		3.0	2.5	67	59.4	46	0.08	56.4
37	1206-	7301	3.2	2.0	48	53.1	56	0.04	57.6
	1214		3.2	2.0	57	56.7	54	0.04	54.4
37	1157-	7203	8.2	5.0	68	47.5	72	0.04	51.1
	1159		8.2	5.0	64	53.5	52	0.04	50.4
56	1295-	7501	1.5	2.0	38	56.2	70	0.05	57.2
	1299		1.5	2.0	34	57.3	75	0.05	58.3
56	1261-	7501	4.0	3.5	105	54,2	54	0.05	56.1
	1264		4.0	3.5	80	56.3	53	0.05	56.1
56	1452-	7501	5.5	3.5	73	47.6	75	0.05	47.3
	1454		5.5	3.5	81	46.1	61	0.05	47.2

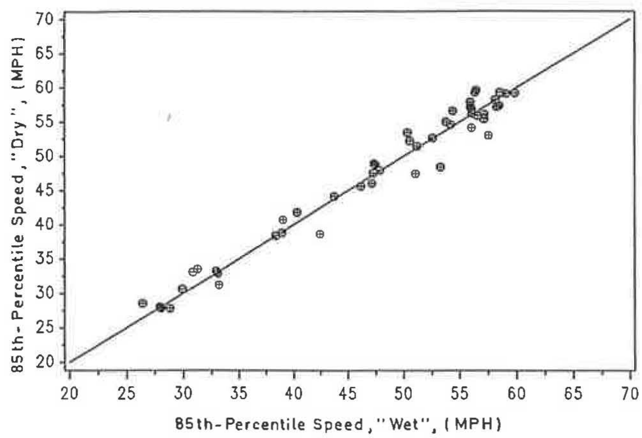

FIGURE 2 Plot relating 85th-percentile speeds on dry pavements to those on wet pavements.

on wet pavements, the Kolmogorov-Smirnov (K–S) two-sample statistical test was used because a priori knowledge of specific population distribution characteristics is not required. This test is performed by statistically examining the cumulative frequency distributions of both the dry and wet test data. The K–S test will detect changes (or differences) in the shape of the distributions (e.g., skewed left to skewed right and bell shaped to skewed) as well as shifts in central tendency without shifts in shape (*27–29*).

The null hypothesis (H_0) tested with the speed data was as follows: "There is no significant difference between the distribution of operating speeds on dry and wet pavements." The test was conducted at the 95 percent level of confidence.

For the operating speed data, (a) if the two samples have in fact been drawn from the same population distribution, then the cumulative distributions of both samples may be expected to be fairly close to each other in as much as they both should show only random deviations from the population distribution, and (b) if the two sample cumulative distributions are too far apart at any point, the samples may come from different populations. Thus, a large enough deviation between the two sample cumulative distributions is evidence for rejecting the null hypothesis (*27–29*).

In order to apply the K–S two-sample test, a cumulative frequency distribution is made for each sample of observations using the same intervals for both distributions. For each interval, then, one step function is subtracted from the other. The test focuses on the largest of these observed deviations.

Let $S_{n1}(X)$ be the observed cumulative step function for the sample corresponding to dry, that is, $S_{n1}(X) = K/n_1$, where K is the number of observations equal to or less than X. Let $S_{n2}(X)$ be the observed cumulative step function of the sample corresponding to wet, that is, $S_{n2}(X) = K/n_2$. Now the K–S two-sample test focuses in the one-tailed test (in the predicted direction) on

$$D = \text{Max}\,(S_{n1}(X) - S_{n2}(X)) \tag{3}$$

and in the two-tailed test (irrespective of direction) on

$$D = \text{Max}\,|S_{n1}(X) - S_{n2}(X)| \tag{4}$$

TABLE 2 CRITICAL VALUES (D_c) IN THE KOLMOGOROV-SMIRNOV TWO-SAMPLE TEST (*28*)

Level of Significance	Value of D so large as to call for rejection of H_0 at the indicated level of significance, where D = maximum $\lvert S_{n1}(X) - S_{n2}(X)\rvert$
.10	$1.22 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$
.05	$1.36 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$
.025	$1.48 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$
.01	$1.63 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$
.005	$1.73 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$
.001	$1.95 \cdot \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}}$

In the one-tailed test, the alternative hypothesis (H_1) is that the population values from which one of the samples was drawn are stochastically larger than the population values from which the other sample was drawn, whereas in the two-tailed test, H_1 is simply that the two samples are from different populations.

An example application of the results of the K–S test of operating speeds on dry versus wet pavements follows.

Set the number of pairs (n_1, n_2) of operating speed values on dry and wet pavements (for both directions of traffic) equal to 48 and the level of significance $\alpha = 0.05$. In the null hypothesis (H_0), the operating speeds on dry and wet pavements do not differ. However, for the alternative hypothesis (H_1) the operating speeds on dry and wet pavements do differ. Because H_1 does not state the direction of the predicted differences, the region of rejection is two-tailed (Equation 4). For the sampling distribution, Table 2 presents the critical values (D_c) of (D) in the K–S two-sample statistical test. If $D > D_c$, then the distribution of one group of speed data is significantly different from the distribution of the second group. Table 3 indicates that the largest discrepancy between the two (dry and wet) cumulative frequency distributions is $D = 2/48 = 0.0417$, in the operating speed range of 46 to 50 mph. Reference to Table 2 reveals that when the number of pairs (n_1, n_2) of operating speed values is 48, $D_c = 0.2776$ for level of significance $\alpha = 0.05$. Therefore, because $D = 0.0417 < D_c = 0.2776$, it can be concluded that operating speeds on dry pavements are not statistically different from operating speeds on wet pavements, at least on the basis of this research investigation.

From the statistical tests, the relationship between operating speed and degree of curve (Equation 2) is valid both for dry and wet pavements so long as the visibility is not appreciably affected by heavy rain. This conclusion is substantiated by the results of a study conducted in the Federal Republic of Germany (*25*), which found that a significant decrease in operating speeds was observed only for high precipitation levels combined with highly reduced visibility conditions.

Ample evidence exists to indicate that wet pavement does not have a great effect on operating speed and that drivers

TABLE 3 RESULTS OF THE KOLMOGOROV-SMIRNOV TEST

OPERATING SPEED RANGES (mph)	$S_1(X)$	$S_2(X)$	$\lvert S_1(X) - S_2(X)\rvert$
> 26-30	4/48	5/48	1/48
> 30-34	10/48	10/48	0/48
> 34-38	10/48	10/48	0/48
> 38-42	15/48	14/48	1/48
> 42-46	17/48	16/48	1/48
> 46-50	24/48	22/48	2/48
> 50-54	29/48	29/48	0/48
> 54-58	42/48	42/48	0/48
> 58-62	48/48	48/48	0/48

will not adjust their speeds sufficiently to accommodate inadequate wet pavement on curves in particular. Drivers do not seem to recognize the fact that because of the lower coefficients of friction on wet pavements as compared with dry, wet pavements could lead to critical driving maneuvers, or even accidents. For passenger cars, the expected operating speed on wet or dry pavements can be determined by applying the nomograph for the relationship between degree of curve and 85th-percentile speed from Figure 3.

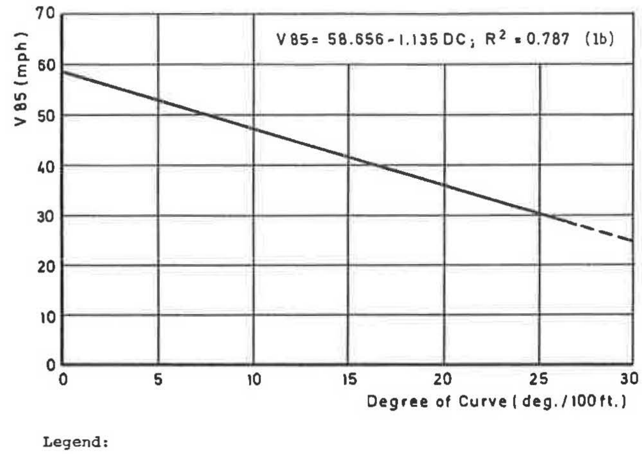

FIGURE 3 Nomogram for evaluating operating speeds of passenger cars as related to degree of curve.

IMPLEMENTATION OF THE RESULTS FOR DESIGN PURPOSES

An international review of existing design guidelines (*2,16–20,30*) has shown that, to gain safety advantages, European countries directly or indirectly address three design issues in their guidelines much more explicitly than U.S. agencies. German, Swedish, and Swiss designers, for instance, are provided with geometric criteria, which direct them toward

1. Achieving consistency in horizontal alignment,
2. Harmonizing design and operating speeds on wet pavements, and
3. Providing adequate dynamic safety of driving.

For example, when consistency between successive design elements is not present, or a harmony between design speed and operating speed does not exist at a certain curved section, or an adequate dynamic safety of driving cannot be provided because of a reduction in friction factors because of wet pavement conditions (*15*), critical driving maneuvers may occur.

Providing an adequate dynamic safety of driving was discussed during the 69th Annual Meeting of the Transportation Research Board, January 1990 (*9*). Achieving consistency in horizontal alignment and harmonizing design and operating speeds on wet pavements were the subjects of several reports, publications, and presentations—for example, for the National Science Foundation (*3*), for the New York State Governor's Traffic Safety Committee (*4,5*), for the Transportation Research Board (*6,7,31,32*), for the Ohio Transportation Engineering Conference (*33–36*), for the International Road Federation (*8,30*), for the Swedish Road and Traffic Research Institute (*37*), for the International Road and Traffic Conference in Berlin (*24*), and for the German research community (*11*).

For achieving consistency in horizontal alignment, the following are recommended: (a) processes for evaluating horizontal design consistency and inconsistency, and (b) recommendations for achieving good and fair design practices, as well as recommendations for detecting poor designs. In harmonizing design and operating speeds on wet pavements, the review of current design practices and recommendations indicate that (a) because of the lower coefficients of friction on wet pavements as compared with dry, the wet condition should govern in determining the design speed (V_d); (b) the design speed should be constant along longer roadway sections; and (c) the design speed and the 85th-percentile speed ($V85$) on wet pavements must be well balanced to ensure a fine tuning between road characteristics, operating speed, and driving dynamics. For instance, studies (*14,38,39*) have shown that the design speed concept allows the building in of critical inconsistencies into the horizontal alignment, for example, between the flatter and sharper portions of the highway, when the 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, which may in turn lead to hazardous driving maneuvers. In addition, a tendency exists for some drivers to travel faster than the design speed on which the original design of the road section was based by substantial amounts, especially at lower design speed levels. This tendency points to the desirability that harmonizing design speed and operating speed is an important goal to be considered in new designs, redesigns, and rehabilitation strategies of two-lane rural highways.

In order to achieve these goals of achieving consistency in horizontal alignment and harmonizing design speed and operating speed, the following recommendations were elaborated (*6,8*):

1. Assess the road section where new designs, major reconstructions, or redesigns, for example, in case of resurfacing,

restoration, and rehabilitation (RRR) projects, may be considered.

2. Determine for this road section the degree of curve (DC) of each curve within the section, and the existing tangent lengths.

3. Determine the expected 85th-percentile speed for each curve, in relation to degree of curve, and for any tangents (DC = 0°), by applying Figure 3. The tangent must be of a certain length to be regarded in the design process, as discussed by Lamm et al. (*7*).

4. Calculate the change in degree of curve (ΔDC) and the change in operating speed ($\Delta V85$) between successive design elements, for example, between tangent and curve or curve and curve.

5. Calculate the difference between the 85th-percentile speed ($V85$) and the existing or selected design speed (V_d) for the investigated curve or tangent.

6. Determine the design category of the section according to the following recommendations, which are based on comparative analyses of accident rates for different degree of curve classes between successive design elements on the 322 investigated two-lane rural highway sections in New York (*6,8*).

Good Designs

Consistency Criterion

The change in degree of curve is $\Delta DC \leq 5°$ and the change in operating speed is $\Delta V85 \leq 6$ mph (10 km/hr) between successive design elements.

Design Speed Criterion

The difference between operating speed and design speed is $V85 - V_d \leq 6$ mph (10 km/hr) for the investigated curve or tangent. For these road sections, consistency in horizontal alignment exists and no improvements in geometric design would be necessary. No adaptations or corrections between design speed and operating speed have to be conducted. New designs should always be related to this case.

Fair Designs

- Consistency Criterion. The change in degree of curve is $5° < \Delta DC \leq 10°$ and the change in operating speed is 6 mph $< \Delta V85 \leq 12$ mph (20 km/hr) between successive design elements.
- Design Speed Criterion. The difference between operating speed and design speed is 6 mph $< V85 - V_d \leq 12$ mph for the investigated curve or tangent.

These road sections exhibit at least minor inconsistencies in geometric design. Normally, correcting the existing alignment is not necessary because low-cost projects such as traffic warning devices may, to a certain extent, be successful in correcting these defects. For instance, RRR improvements can be installed that consider appropriate recommended speeds, unless a safety problem has been documented. Despite traffic warning devices, road sections with changes in degree of curve that fall into the range of 5° to 10° have average accident rates that are about twice as high as those falling into the range of good design (*6,8*).

Superelevation rates in curves or curved sections should be related to the expected 85th-percentile speeds with respect to degree of curve, corresponding to Figure 3, and not to the design speed. Adequate driving dynamic safety is inferred as being provided under wet pavement conditions. The same holds true for calculating minimum stopping sight distances in curved and tangent sections.

Poor Designs

- Consistency Criterion. The change in degree of curve is $\Delta DC > 10°$ and the change in operating speeds on wet pavements is $\Delta V85 > 12$ mph between successive design elements.
- Design Speed Criterion. The difference between operating speed and design speed is $V85 > V_d > 12$ mph for the investigated curve or tangent.

These road sections represent strong inconsistencies in horizontal geometric design, combined with those breaks in the speed profile that may lead to critical driving maneuvers, especially under wet pavement conditions. Normally, for example, even high-cost RRR projects such as redesigns of at least hazardous road sections should be recommended, unless there is no documented safety problem. Road sections with changes in degree of curve that fall into the range of poor design normally have average accident rates that are more than four times as high as those falling into the range of good design (*6,8*).

The 85th-percentile speed should not be allowed to exceed the design speed by more than 12 mph (20 km/hr). If such a difference occurs, normally the design speed should be increased. For example, redesigns of at least hazardous road sections are recommended.

CONCLUSION

The impact of design parameters and traffic volume on operating speeds of passenger cars under free-flow conditions was evaluated. The data base consisted of 322 curved roadway sections of varying degrees of curve of two-lane rural highways in New York state. Among the parameters considered, degree of curve, length of curve, superelevation rate, gradient, sight distance, lane width, shoulder width, posted recommended speed, and AADT, only degree of curve was able to explain most of the variation in 85th-percentile speeds on dry pavements. The other parameters helped the regression model, but the equation did very well even without them.

Also examined was the effect of wet pavements on the 85th-percentile speeds of passenger cars. On all occasions, the surfaces were wet and rain was falling from a sprinkle to moderately heavy rain, but on no occasion did it rain so hard as to affect visibility appreciably. Minimum sight distances of about 450 to 550 ft, which represent the limiting values of stopping sight distances for a design speed of 55 mph, had to be provided.

Operating speeds on dry pavements were not statistically significantly different from operating speeds on wet pavements and drivers do not adjust their speeds sufficiently to accommodate adequate wet pavement on curves in particular. Drivers did not recognize the fact that friction supply is significantly lower on wet pavements as compared with dry. Furthermore, drivers reduce their speeds not so much on account of the danger created by lower skid resistance values on wet pavements, but rather because of limited sight distances because of heavy rain. By not adapting to wet roadway conditions, drivers will run a high risk of being involved in a traffic accident.

For the implementation of the results for design purposes, recommendations for achieving consistency and detecting inconsistencies in horizontal alignment as well as recommendations for harmonizing design speed and operating speed as related to wet pavement conditions were made for good, fair, and poor design practices. These recommendations are important tasks in modern highway design and redesign strategies for improving traffic safety.

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