Analysis of Vehicle Operations on Horizontal Curves

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A study was conducted to quantify the effects of horizontal curve features on such operational variables as changes in vehicle speeds and vehicle encroachments over the centerline and edgeline. This information was considered important in determining curve design criteria that would lead to effective safety and operational improvements at current curve sites. The data included geometric, traffic, and operational measures from a data base of 78 curve sites in New York State. Various statistical procedures were used, including linear regression analyses, analyses of operations by differing groups of geometric conditions, residual analyses, and locally weighted nonparametric regression. It was found that, as curves become sharper, there is a proportionally greater increase in speed reduction and edgeline encroachments on the inside lane (i.e., the lane on a curve where the motorist must steer to the right). Centerline encroachments in the outside lane increase more drastically than those on the sharper curves to the right. These findings support the contention of drivers cutting the curve short, which can result in run-off-road crashes on the inside of the curve as well as head-on and opposite-direction–sideswipe crashes with oncoming motorists. Appropriate curve design guidelines are discussed that may help to minimize these operational and potentially accident-related trends.

One of the major safety and operational problems facing motorists on two-lane rural highways relates to horizontal curves. Studies have consistently found that curves account for a higher rate of crashes and for greater crash severity than tangent sections of highway (*1*,*2*). The increased crash rates on curves are to be expected, because a curve requires a driver to perceive a change in roadway alignment and to take appropriate action, such as braking and steering changes. On sharp curves or under adverse environmental conditions (e.g., at night during rain or in fog), these tasks can be quite difficult.

Highway agencies are responsible for identifying curves that have safety and operational problems and for making necessary improvements. Although crash data may be useful in providing insights into such problems, crashes are typically rare at a given curve site. In fact, Zegeer et al. (*1*) found an average of only about one crash per curve at 10,500 curve sites on rural two-lane roads in Washington State during a 5-year period. Thus, the sample of crashes at a given site is often small and most likely will not reveal the full picture of safety and operational problems for drivers who encounter the curve.

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The collection and analysis of traffic operational data on a sample of curves can be useful in several respects. For example, it can provide insights into how drivers react to various curve geometrics. Traffic operational measures on curves can also indicate the adequacy of the curve design in handling the traffic mix on the curve and possibly help to suggest accident problems that may result. Such knowledge can be useful in selecting appropriate roadway improvements on existing curves and better designs for alignment on new roadways (*3*).

The operational characteristics of various horizontal curve features were investigated. The operational measures of concern included speed changes and vehicle encroachments over the centerline and edgeline. Figure 1 shows edgeline and centerline encroachments in a curve to the right (i.e., the inside of the curve). Geometric and roadway features that were analyzed included degree of curve, length of curve, superelevation deviation, vertical alignment (grade), and roadside hazard. The data were taken from a data base of 78 curve sites in New York State and included geometric, traffic, accident, and operational variables.This data base was developed by Terhune and Parker (*4*). All 78 study sites were on two-lane rural roadways. Various statistical procedures were used to correlate operational measures with curve geometrics, resulting in recommendations for improved curve designs to minimize the operational problems that were identified.

BACKGROUND

Numerous studies have been conducted in recent years to record vehicle operations on curves. Glennon et al. (*2*) monitored vehicle speeds and lateral placement through five horizontal curves in Illinois and Ohio. They found that some drivers overshoot the curve radius, producing minimum vehicle path radii sharper than the highway curve. This tendency was found to be independent of vehicle speed.

Vehicle speed data were also observed by Glennon et al. for free-moving vehicles as they traversed 60 curve approaches. The sharpness of the impending curve was the factor most associated with speed changes by the drivers. Drivers tended to begin adjusting their speeds only as the curve became imminent, and speed reduction increased linearly with increasing degree of curve. Only a slight difference in speed changes was found for narrow versus wide roadways.

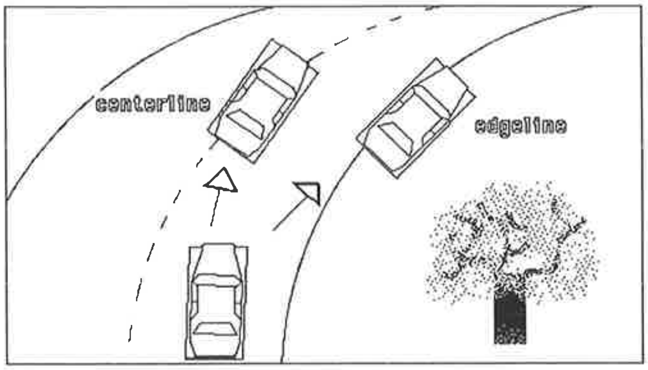

FIGURE 1 Centerline and edgeline encroachments in a curve to the right.

Jennings and Demetsky (*3*) collected traffic volume, vehicle speed, and lateral placement data at five curve sites in Virginia. Although their primary objective was to evaluate the effects of post-mounted delineator systems, they also analyzed driver responses in general at eight other sites. Similar average speeds, vehicle placements, and centerline encroachments were observed at various sites that had similar delineators. Vehicles were found to travel further from the roadway edge when delineation was present.

Terhune and Parker (*4*) collected various operational measures at 78 horizontal curve sites. Those measures found to be related to accident rate included traffic volume, average speed reduction, rate of centerline encroachments, and edgeline encroachments. However, none of the operational measures were inclulded in the best-fitting accident predictive models.

Datta et al. (*5*) collected several operational measures at 25 rural, two-lane curve sites as part of a study on accident surrogates. Speed differential and traffic volume were the only operational measures included in any of the best-fitting accident predictive models, along with several nonoperational variables (e.g., sideslope, degree of curve, and superelevation error).

Several studies have also used operational measures to evaluate the effectiveness of curve delineation treatments. For example, Rockwell et al. (*6*) evaluated curve modifications on horizontal curves. Operational measures collected for traffic stream drivers included vehicle speed profiles and severe lateral displacement. Although signing treatments were largely ineffective, reductions in speed variance resulted from some of the modifications, such as pavement markings.

Rockwell and Hungerford (*7*) tested six delineation treatments at rural curve sites in Ohio. Some treatments (e.g., post delineators, raised pavement markers, and transverse pavement stripes) were recommended at selected curve sites with a high rate of nighttime crashes and a high proportion of transient drivers.

Although a number of studies have been conducted on vehicle operations at horizontal curve sites, few have analyzed the influence of various curve design features on vehicle operations. These geometric features of curves and their effects on vehicle operations are addressed in the following paragraphs. The results of the analysis are then used to recommend design improvements for new and existing horizontal curves.

DATA

As explained previously, the data base was developed by Terhune and Parker for a study to identify accident surrogates, that is, to find which geometric and operational measures were related to accident experience and therefore could be used as measures of high accident potential at curve sites. In that study, accident prediction models were developed with various geometric and operational measures as independent variables, resulting in degree of curve and average daily traffic (ADT) being the variables most strongly related to crash rates. In the study reported here, accident data were not used, but relationships between roadway and geometric features and operational measures were determined.

The field operational data were typically collected during daylight hours on dry pavement. Encroachment and speed change data were collected by a two-person crew from a concealed location at each site. Operational (i.e., dynamic) data were collected in half-hour increments until 4 hr of data were collected per curve site. Traffic volumes and edgeline and centerline encroachments were counted for each lane. An encroachment was recorded each time a vehicle tire passed over the roadway edgeline or centerline on the curve. Encroachment counts were divided by traffic volume to yield encroachment rates. Because encroachments obviously occur from either the inside lane or outside lane of a curve, the encroachment data were categorized according to these lane characteristics.

Speed data were also collected on selected isolated vehicles—those with a headway of 9 sec or more between leading and trailing vehicles—using a radar meter at points 250 ft before the midpoint of the curve and at the midpoint. The desired measure of speed reduction was the difference between the two measurements.

As mentioned, the geometric and roadway features that were analyzed (referred to as nonoperational variables) included degree of curvature, length of curve, superelevation deviation, vertical alignment (grade) and roadside hazard rating. The roadside hazard rating was a 6-point rating scale, which described the roadside conditions within 15 ft of the edge of the paved surface. The scale was defined as follows:

Roadside Condition	*Rating*
Clear, no fixed objects, fairly level terrain	1
Vegetation or yielding objects, no rigid fixed objects, fairly level terrain	2
Isolated rigid fixed objects, fairly level terrain	3
Ditch throughout most of curve, no embankment or sideslope > 3:1	4
Embankment or sideslope > 3:1	5
Numerous or continuous rigid fixed objects	6

The operational measures used were selected because they are important in determining how drivers maneuver their vehicles on curves of differing roadway and geometric conditions. Such measures are not necessarily related directly to vehicle crashes, although there are at least some logical associations between unsafe vehicle maneuvers and the likelihood of a collision. For example, frequent or several encroachments over the centerline could lead to head-on crashes, particularly on curve sites with moderate-to-high volumes of oncoming vehicles. High rates of edgeline encroachments may indicate that drivers are approaching the curve too fast or are surprised by the sharpness of the curve. Speed change is related to both the approach speed and the speed in the curve. Large speed reductions by vehicles going into a curve indicate that drivers are decelerating quickly to negotiate the curve. Such a driving task may be even more difficult at night or under wet or icy pavement conditions, which could indicate a high potential for crashes.

ANALYSIS AND RESULTS

Descriptive Analyses

Descriptive analyses were conducted for the New York State surrogate data base. Frequency listings for operational and nonoperational variables of interest were examined, as well as Pearson chi-square (X^2) measures of association. The frequency listings proved useful in determining the formation of category levels for certain variables later categorized. Pearson X^2 measures of association were calculated between each operational variable and each nonoperational variable, and the significances of each association was determined (see Table 1). Included in the table are both the value of X^2 divided by the degrees of freedom (to normalize values for comparisons among cells in the table) and the p value for examining the strength of the association.

Average speed reduction was found to be significantly associated with degree of curvature (for $\alpha = 0.05$). Centerline encroachments for curves to the right were significantly associated with grade. Centerline encroachments for curves to the left were significantly associated with degree of curvature, curve length, and grade. Edgeline encroachments on the inside lane were significantly associated with superelevation deviation and marginally significantly associated with degree of curve ($p = .095$) and grade ($p = .062$). Edgeline encroachments on the outside lane had no significant association with any of the nonoperational variables.

TABLE 1 MEASURES OF ASSOCIATION BETWEEN OPERATIONAL AND NONOPERATIONAL VARIABLES

Roadway Feature	Speed Reduction	Centerline Encroachment		Edgeline Encroachment	
		Inside	Outside	Inside	Outside
Degree of Curve	3.6* 0.03 +	2.1 0.33	6.1 0.002	2.4 0.095	0.7 0.50
Curve Length	0.3 0.72	0.5 0.61	4.5 0.01	1.5 0.22	0.6 0.55
Superelevation Error	2.7 0.07	1.1 0.34	0.5 0.63	6.2 0.04	0.5 0.58
Shoulder Width	1.8 0.16	0.7 0.49	0.7 0.50	0.7 0.52	0.6 0.55
Grade	1.1 0.30	10.8 0.001	6.3 0.01	1.7 0.06	0.0 0.92
Roadside Hazard: Outside	1.1 0.32	1.2 0.30	0.7 0.52	0.3 0.73	0.1 0.88
Roadside Hazard: Inside	2.3 0.10	2.4 0.10	0.3 0.74	0.5 0.58	0.3 0.74

*X^2/df +p-value

As an alternative method for exploring the data, averages for each of the nonoperational variables were compared across low and high rates of the operational (or outcome) variables. After the values of the four encroachment variables were normalized by traffic volume (number of vehicles per hour passing through the curve in either the inside or outside lane yielding encroachment rates), they along with speed reduction were dichotomized across each variable. The lower values (values below and including the median value of each variable) comprised one group, whereas the other group contained the higher values (values above the median). Table 2 presents means and standard errors for each of the seven nonoperational variables within the two subgroups of each of the operational variables. This breakdown allowed for visual comparison of the means of the nonoperational variables between high and low categories for each operational variable. In a sense, this method is similar to discriminant analysis in that it examines levels (averages) of the nonoperational variables that are associated with low versus high outcome (operational) groups.

In Table 2, consider the operational measure of average speed reduction. Of the sample curve sites, half had low speed reductions (below 1.7 mph) and half had high speed reductions (at least 1.7 mph). Average curvature, curve length, and other roadway features were computed within these low and high categories of speed reduction. For example, curve sites with low speed reductions had an average curvature of 4.22 degrees, compared with 6.42 degrees for the curve group with high speed reductions. In other words, greater speed reductions were associated with sharper degrees of curve.

In Table 2, the greater speed reduction group is associated with shorter average curve length (714.9 ft) than the lower speed reduction group (764.7 ft), probably because greater speed reductions occur with sharper curves and because sharp curves are usually shorter than mild curves. Other roadway features associated with greater speed reductions include greater superelevation deviation (i.e., more superelevation deficiency), wider shoulders, and steeper grades. The effect of roadside hazard on speed reduction is unclear.

Similar types of data summaries are presented in Table 2 for centerline and edgeline encroachments. Higher centerline encroachment rates for curves to the right were observed for narrower shoulders and steeper grades. Also, curves with higher roadside hazard ratings resulted in greater centerline encroachment rates for curves to the right, perhaps because motorists tend to shy away from the edge of the pavement on curves where roadside hazards are greater (e.g., large trees or steep sideslopes adjacent to the roadway).

Centerline encnroachment rates for curves to the left are also presented in Table 2. Higher encroachments occur for sharper curves, shorter curves, narrower shoulders, and steeper grades. These results indicate that vehicles in curves to the left or right are more likely to encroach the centerline when confronted with curves having more restrictive geometrics.

The frequent occurrence of centerline encroachments on sharp curves deserves further discussion. Crash data reveal that run-off-road crashes are much more frequent on horizontal curves than are head-on crashes. For example, Zegeer et al. (*1*) found that fixed-object plus rollover crashes accounted for 57.1 percent compared with only 8.2 percent for head-on plus opposite-direction–sideswipe crashes. Thus, a

TABLE 2 MEANS AND STANDARD ERRORS OF NONOPERATIONAL VARIABLES DICHOTOMIZED BY OPERATIONAL VARIABLES

Roadway Feature	Average Speed Reduction: Curve to the Left (mi/h)		Centerline Encroachment Rates (No/Hr/ADT)				Edgeline Encroachment Rates (No/Hr/ADT)			
			Curve to the Right		Curve to the Left		Curve to the Right		Curve to the Left	
	<1.7* (31)**	1.7+ (31)	<0.13 (27)	0.13+ (26)	<0.24 (31)	0.24+ (31)	<0.24 (32)	0.24+ (27)	<0.11 (37)	0.11+ (26)
Degree of Curve	4.22*** 0.29+	6.42 0.60	4.69 0.35	4.68 0.36	4.35 0.32	6.13 0.60	4.09 0.23	5.29 0.42	5.38 0.52	5.09 0.45
Curve Length	764.7 63.52	714.9 52.28	788.1 57.86	758.5 69.76	875.0 56.67	639.0 58.38	844.4 59.99	700.0 64.72	719.0 46.15	806.5 81.24
Superelevation Error	0.04 0.004	0.05 0.003	0.04 0.004	0.04 0.004	0.04 0.004	0.04 0.003	0.05 0.004	0.04 0.003	0.04 0.003	0.04 0.004
Shoulder Width	7.74 0.29	8.48 0.31	8.56 0.25	7.85 0.36	8.39 0.23	7.88 0.36	8.41 0.29	8.00 0.34	8.11 0.24	8.15 0.39
Grade	1.39 0.11	1.65 0.14	1.26 0.11	1.62 0.15	1.35 0.12	1.66 0.13	1.19 0.11	1.69 0.14	1.38 0.11	1.69 0.15
Roadside Hazard Outside	3.81 0.29	3.45 0.33	3.26 0.34	3.80 0.36	3.52 0.35	3.66 0.27	3.26 0.33	3.80 0.37	3.84 0.30	3.23 0.31
Roadside Hazard Inside	3.48 0.28	3.65 0.36	3.07 0.33	3.65 0.36	3.71 0.32	3.41 0.32	3.37 0.35	3.35 0.35	3.68 0.31	3.38 0.32

*50 percent of the sample had speed reductions of less than 1.7 mph

**Number of curves in operational variable group

***Mean +Standard error Data not available for several sites

greater number of edgeline encroachments (i.e., related to run-off-road crashes) than centerline encroachments should be expected.

To help explain this apparent inconsistency, it should be considered that many of the centerline encroachments may be controlled, or intentional, encroachments. In other words, on a curve to the left, some drivers will intentionally cut the corner while driving across the centerline if they see no oncoming vehicles. Although this maneuver seems dangerous, many rural roads have low traffic volumes and thus opposing vehicles are relatively infrequent. Further, if a vehicle encroaches the centerline in a curve to the right because of excessive speed while another vehicle is approaching, the driver of the oncoming vehicle can often take evasive action and avoid the crash.

The factors related to edgeline encroachments for vehicles on curves to the right and left are also presented in Table 2. Factors related to higher edgeline encroachment rates for curves to the right include sharper curves (5.29 versus 4.09 degrees), shorter curves (700 versus 844 ft), slightly narrower shoulders (8.0 versus 8.4 ft), and steeper grades (1.69 versus 1.19 percent). For vehicles on curves to the left, higher edgeline encroachments were found for steeper grades (1.69 versus 1.38 percent). However, sharper curves were surprisingly not associated with more edgeline encroachments. As mentioned previously, for vehicles on curves to the left, sharper curves (6.10 versus 4.35 degrees) were associated with greater centerline encroachments, which would be consistent with the lack of increased edgeline encroachments for those vehicles. This finding may seem counterintuitive because vehicles in sharper curves to the left may be expected to run off the road on the right rather than encroach the centerline. Although such edgeline encroachments occur with some frequency (and sometimes lead to run-off-road crashes), the drivers appear to cut the curve more often than encroach the edgeline for these sharper curves. This finding may also indicate that, although edgeline encroachments are relatively rare, their occurrence may more often result in a crash than centerline encroachments because the latter will lead to a multivehicle crash only if an oncoming vehicle is present.

The relationship of edgeline encroachments to crashes may depend largely on roadway width. An edgeline encroachment on a curve with narrow lanes (e.g., no more than 10 ft) and no shoulder can often result in a driver's loss of control and a fixed-object crash, particularly if the sideslope is steep or there are fixed objects near the roadway. On curves with wide lanes and wide paved shoulders, an edgeline encroachment presents a much lower chance of a crash.

The key results of Table 2 are summarized in Table 3. The influence of various roadway features on vehicle operations can easily be seen. For example, as discussed previously, the greater amount of average speed reduction is associated with sharper and shorter curves, more superelevation deviation, and steeper grades. Likewise, steeper grades on curves are associated with an increased incidence of each of the operational measures, which is important in explaining operational problems on curves. An increased level of hazard in curves to the right is related to an increased incidence of vehicles on these curves that encroach the centerline. This finding may indicate a tendency to steer away from trees, steep slopes, and other roadside hazards on the right when going around a curve to the right.

TABLE 3 SUMMARY OF ROADWAY FEATURES ASSOCIATED WITH HIGHER INCIDENCE OF OPERATIONAL MEASURES

Roadway Feature	Average Speed Reduction	Centerline Encroachments		Edgeline Encroachments	
		Curve to The Right	Curve to The Left	Curve to The Right	Curve to The Left
Sharper Degree of Curve	•		•	•	
Shorter Curve Length	•	•	•	•	
More Superelevation Deviation	•				
Narrow Shoulder Width		•	•	•	
Steeper Grade	•	•	•	•	•
Greater Roadside Hazard: (Outside Lane)		•		•	
Greater Roadside Hazard: (Inside Lane)		•			

Regression Analyses

Analysis for Entire Sample of Curves

Most of the measures of association discussed previously are essentially correlation statistics, which are useful indicators in determining which nonoperational variables (e.g., degree of curve) might best account for the amount of variation in the operational variable values (e.g., speed reduction). To help explain this variation, least squares regression analyses were carried out using the information obtained from the Pearson X^2 analyses.

Scatterplots of actual values were constructed of each operational variable (vertical axis) versus each promising nonoperational variable (horizontal axis). Scatterplots using degree of curve as the nonoperational variable are shown in Figures 2–4 for speed reduction, centerline encroachments for curves to the right, and edgeline encroachments for curves to the right, respectively. Included in each figure is a nonparametric regression curve fitted by a locally weighted regression procedure (LOWESS), which is discussed later.

A variety of models were considered, but only two are noteworthy. On the basis of R^2 values and significance of parameter estimates (using SAS PROC GLM), these two models were centerline encroachments for curves to the left versus degree of curve and average speed reduction versus degree of curve—with R^2 values of 0.37 and 0.30, respectively. Because relationships are being investigated rather than using regression as a prediction model, the modest R^2 values are acceptable.

Analysis Within Mild Versus Extreme Roadway Conditions

It was hypothesized that a more definitive relationship might be seen between the operational and nonoperational variables if the curves were dichotomized into seemingly mild versus hazardous conditions. Thus, the data were categorized into

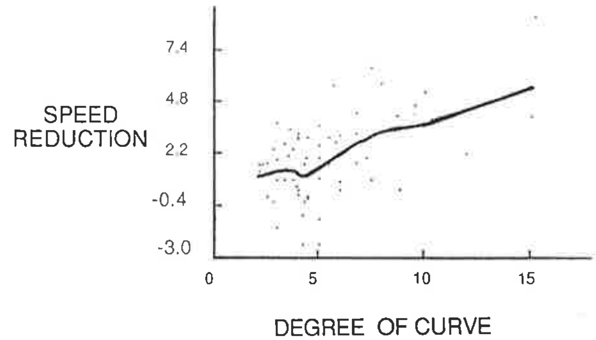

FIGURE 2 Speed reduction versus degree of curve.

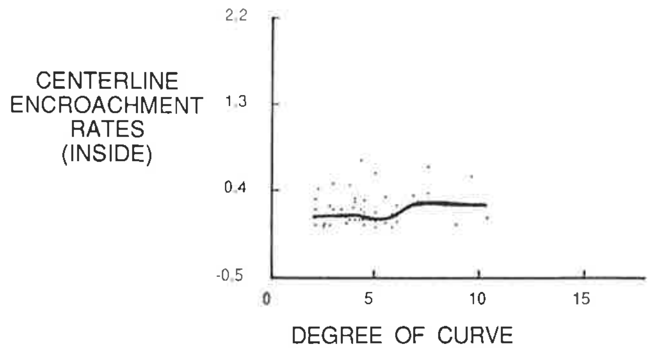

FIGURE 3 Centerline encroachment rates on curves to the right versus degree of curve.

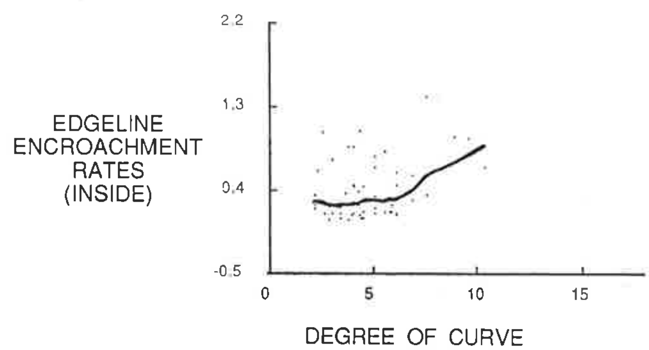

FIGURE 4 Edgeline encroachment rates on curves to the right versus degree of curve.

two groups of curves on the basis of certain ranges of the following nonoperational variables:

- Superelevation deviation [termed "superelevation error" by Terhune and Parker (*4*)],
- Grade, and
- Roadside hazard rating.

The two groups created from these three variables are referred to as being favorable or unfavorable. The unfavorable group consisted of curves meeting one or more the following criteria:

- Superelevation error greater than 0.05,
- Grade rating of 3 (i.e., very steep), or
- Roadside hazard rating of 6 (i.e., most hazardous).

Plots were constructed within each group using degree of curve as the main nonoperational variable of interest (see Figures 5 and 6). As expected, associations between the degree of curve and the operational variables were much stronger in the unfavorable group. However, the data are still rather dispersed, pointing to the need for an analysis of residuals (i.e., differences between observed and predicted values).

Residual Analyses

Residual analyses were conducted for the univariable models formulated in the favorable and unfavorable curve groups. These analyses attempted to determine whether certain least squares regression assumptions were invalidated. Plots of the residuals versus the observed values for the combined curve group suggested that there is a violation of one of the regression assumptions because the error variable increases with increasing values of degree of curve. This tendency is indicated by the shape of the residual plot in Figure 7, which, in turn, suggested the use of a variance stabilizing transform. However, these transforms failed to improve on the least squares regression models.

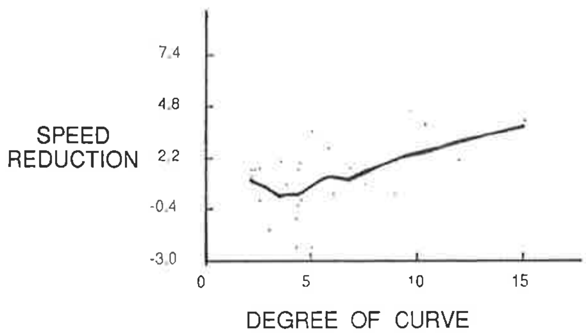

FIGURE 5 Speed reduction versus degree of curve: favorable curve group.

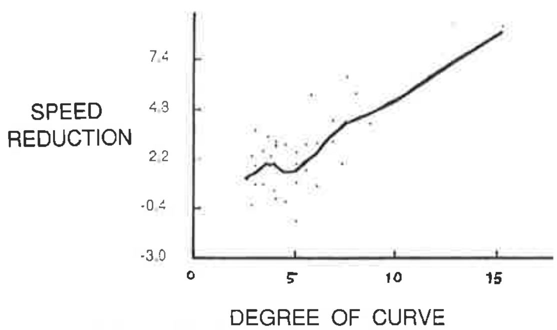

FIGURE 6 Speed reduction versus degree of curve: unfavorable curve group.

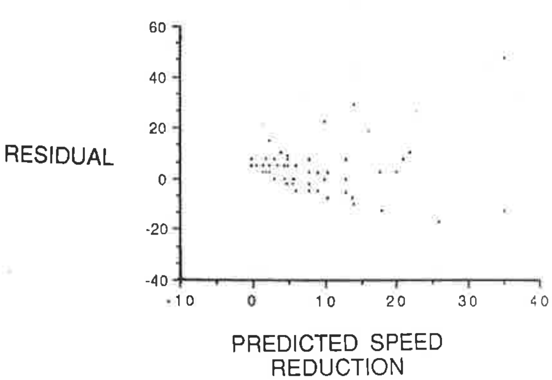

FIGURE 7 Predicted speed reduction versus residual.

Locally Weighted Regression

Because of the extreme amount of dispersion in the data, LOWESS was employed. This method of regression is a nonparametric approach that does not assume constant error variance of the dependent variable as does the method of least squares regression.

The LOWESS technique fits a line within certain groups of points and then joins the lines for each group to form a curve. This technique gives only the shape of the curve. It does not give parameter estimates. Illustrative LOWESS plots of speed reduction versus degree of curve for the favorable and unfavorable groups of curves can be seen in Figures 5 and 6, respectively. Plots for the ungrouped curves (i.e., combining favorable and unfavorable geometric combinations) are depicted in Figures 2–4 for speed reduction.

In view of the various LOWESS plots, an unclear relationship exists between the values of the five operational variables and degree of curve values below 5 degrees. However, a number of the graphs depict a linear relationship when considering curves of 5 degrees and higher, particularly speed reduction and edgeline encroachment rates for inside lanes.

There are relatively few sharp curves (at least 10 degrees) in the sample. The corresponding LOWESS plots in this region would not be as reliable as those for milder curves.

SUMMARY AND CONCLUSIONS

In conclusion, several relationships bear mentioning. Average speed reduction and edgeline encroachments on curves to the right appear to be positively associated with degree of curve for curves about 5 degrees. As curves become sharper, there is a proportionally greater increase in speed reduction and edgeline encroachments for curves to the right. Centerline encroachments on curves to the left also increase more drastically than those on curves to the right.

These results on operational measures support results of the accident analyses presented by Zegeer et al. (*1*). For example, degree of curve is clearly the geometric feature that most adversely affects both accidents and vehicle operations on horizontal curves, with sharper curves producing significantly increased rates of accidents, as well as high rates of speed reductions and vehicle encroachments. The greater incidence of edgeline encroachments for curves to the right combined with increased centerline encroachments for curves to the left supports the contention of drivers undercutting the curve (*2*). This practice can result in run-off-road crashes on curves to the right or head-on and opposite-direction–sideswipe accidents with oncoming motorists on curves to the left.

The results of the operational analysis support the predominance of single-vehicle crashes (i.e., fixed-object and rollover) and opposing multivehicle crashes (i.e., head-on and opposite-direction–sideswipe), which have been found in various curve studies (*1*,*2*) to be overrepresented on curves when compared with tangents. The sharpness of curves in particular is associated with greater speed reductions and encroachments over the centerline and edgeline. To a lesser degree, wide shoulders and less severe grades were associated with fewer operational problems. Such results reinforce the importance of various design features in curve safety and operations.

RECOMMENDATIONS FOR CURVE DESIGN AND UPGRADING

The study findings are of interest in determining appropriate, cost-effective countermeasures to existing curve problems. They are also useful in evaluating the adequacy of current curve design policy and in formulating guidelines for design of high-speed curves.

Of course, countermeasure effectiveness and design standards for curves are largely oriented toward safety. Operational measures of effectiveness are valuable to the extent that they support or clarify what is known about the relationships between curve design features and accidents.

This section presents findings on the subject of curve design for existing as well as new highways. These findings are based not only on the operational studies reported here, but also on separate analyses of accident and roadway data bases (*1*). These analyses, in turn, build on previous research (*2*,*4*).

The operational analyses clearly represent only a few pieces of the puzzle describing the safety and operational characteristics of highway curves. Nonetheless, the findings are important in that they tend to support other key research on safety.

In general terms, it can be concluded that highway curves present special problems to drivers. Curves require drivers to adjust their speed and path. When curves are particularly sharp and when no transition curvature is provided, driver and vehicle behavior problems ensue. Furthermore, when such curves occur in concert with other geometric problems (e.g., steep grades, narrow lanes, narrow shoulders, and hazardous roadsides), accidents are inevitable.

Previous work has led to the following conclusions about treatment of existing curve problems:

1. Flattening an existing sharp curve offers the greatest potential (relative to other improvements) for reducing crash frequency.
2. Roadway widening on curves is effective in producing lower accident rates.
3. The presence of spiral transitions and adequate superelevation is associated with small, but significant, reductions in accidents.
4. Various roadside improvements (e.g., clearing trees near the road, relocating utility poles, and flattening sideslopes) are particularly beneficial at curves.

Cost-Effective Treatments of Existing Curves

Not every sharp curve represents a safety or operational problem, and not every high-accident curve can be treated by geometric or traffic control countermeasures. Although research findings provide insights into curve countermeasures, site-specific study is clearly mandated. Each location is unique in its constraints, physical conditions, and operational characteristics. The study of existing accident patterns, an evaluation of site geometric and roadside conditions, and observations of driver behavior are necessary to adequately identify appropriate treatments at a particular curve site.

Generally, countermeasures fall into three categories: (a) complete reconstruction; (b) physical rehabilitation or partial reconstruction; and (c) low-cost spot improvements, such as signing, marking, and delineation.

Curve reconstruction represents the most costly, but potentially the most effective, means of reducing severe curve accidents. Curve reconstruction may involve flattening of the curve, widening of lanes and shoulders, new pavement, improved roadside, and the addition of a spiral transition curve. The feasibility or cost-effectiveness of total curve flattening and reconstruction depends largely on site-specific conditions. The availability and cost of right-of-way, vertical alignment requirements, environmental impacts, and local access changes would influence any decision to reconstruct a curve.

Curve rehabilitation and partial reconstruction are typically less costly measures than curve flattening or roadway widening and may be highly effective in treating existing curves. Foremost among these is removal of roadside hazards within the area of influence of the curve. Tree removal, utility pole relocation, sideslope flattening, and other improvements may be cost-effective at relatively low traffic volume levels. Resurfacing of the curve to improve skid resistance is also a potential solution. Resurfacing projects can be used to improve the superelevation in the curve, adjust the superelevation transition, pave the shoulder through the curve, clear roadside obstacles, and eliminate pavement edge drop-off conditions. All of these measures can be implemented within existing rights-of-way and with relative ease. The effectiveness of a package of curve rehabilitation countermeasures would, of course, depend on the particular site. TRB *Special Report 214* (*8*) provides useful information about resurfacing, restoration, and rehabilitation.

Such improvements as signing, marking, and delineation are intuitively appealing because of their low cost and ease of implementation. Advance warning signs, centerline and edgeline markings, and special delineation schemes have been tested at high-accident locations. Special attention to signing and marking is important along any highway, particularly at sharp curves. It is clear, however, that the addition of signing, marking, and delineation cannot be expected to solve a safety problem on a poorly designed curve. At the same time, proper signing, marking, and delineation in accordance with the *Manual on Uniform Traffic Control Devices* (*9*) are essential when treating hazardous curves in conjunction with other improvements (e.g., clearing roadsides, widening the roadway, paving the shoulder, flattening the curve, or improving the superelevation). Even if construction or reconstruction of a poorly designed curve is not possible, substandard signing, marking, and delineation should still be improved on hazardous curves.

Design Guidelines for New Highway Sections

Most highway design in the United States is governed by AASHTO procedures, criteria, and design values (*10*). Research from all recent studies on horizontal curves suggests that application of some specific design guidelines would significantly improve the overall quality of horizontal curve design.

For example, designers should provide for consistent roadway sections. By avoiding sharp, isolated curves and by maintaining consistency in the design of superelevation, roadway width, and other features on curves, designers can minimize the element of surprise and better accommodate the difficult speed and path transition behavior required of drivers.

Designers should avoid large central angles wherever possible. Such angles force designers to choose between long curves or sharp curves, both of which present problems. On long curves driver exposure to curve tracking problems (centerline and edgeline encroachments) is longer. On sharp curves tracking and speed transition problems are more severe. A suggested criterion is to avoid central angles greater than 45 degrees.

Designers should minimize the use of controlling curvature (i.e., maximum allowable curvature for a given design speed). Many designers tend to view all curves as equally safe within a given design speed. However, milder curves operate better and tend to have better accident histories. Where controlling curvature is used, designers should pay extra attention to the roadside design (particularly on curves to the left).

Designers should routinely use spiral transition curves, particularly for controlling curves on highways with high design speeds (e.g., 60 mph or greater). The safety effects of spirals have been demonstrated (*1*) and operational benefits of spirals have also been found (*2*). Again, adequate transition design is particularly critical on higher speed alignment.

Designers should routinely provide high-quality roadside designs, particularly on sharper curves. Wider shoulders, flatter sideslopes, and greater roadside clear zones in these areas are essential design features.

Designers should avoid locating other potentially hazardous features at or near horizontal curves, in recognition of driver difficulty in tracking curvature. Features to avoid include intersections, narrow bridges, major cross-section transitions, and driveways. Another potentially hazardous feature is severe reverse curvature with curves in opposing directions separated only by a short tangent alignment.

Designers should provide adequate pavement and shoulder condition, particularly on sharper curves where lateral acceleration and function demand are the greatest. Increasing pavement skid resistance is often an essential curve improvement, especially for curves that have skidding accidents during wet pavement conditions. On highways with unpaved shoulders, consideration should be given to paving the shoulders at the sharper curves. Vertical curvature should be provided such that more than the minimum stopping sight distance is available throughout the curve.

Finally, designers should use an adequate amount of superelevation on all curves.

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