This is an unedited draft reflecting my personal opinions. Ezra Hauer

5. Safety of Horizontal Curves.

E. Hauer, Draft[1], March 24, 2000

There are several element of horizontal alignment that are associated with horizontal curve safety. The safety of a horizontal curve- its accident frequency and severity- is partly determined by features **internal** to it (radius or degree of curve, superelevation, spiral, etc.) and partly by features **external** to it (density of curves upstream, length of the connecting tangent sections, sight distance, etc.) that influence driver expectation and curve approach speed.

5.1. Accidents and degree of curve (or curve radius).

The number of degrees of arc subtended by 100 feet of curve length is called the degree' of a curve (D). The radius of a curve (R) in metres equals 1748/D. Accident occurrence on a curve is believed to be a function of its degree or, equivalently, of its radius.

1953. Raff examined how accident rates depend of the design features of main rural roads using data from a bout 5000 miles of highway in fifteen states. The relationship between the accident rate and degree of curve for three road types is shown in Figure 1 in which U stands for 'undivided', D for 'divided', and CA for 'control of access'. In linear relationship is indicated. An eye-ball fit to the data in Figure 1 is 1.3+0.25D accidents/MVM or 0.8+0.16D accidents/MVkm. Two kind of caution are in order. First, road sections with sharp curves tend to also have narrower lanes and shoulders and unforgiving roadsides. Therefore a univariate representation may be misleading.

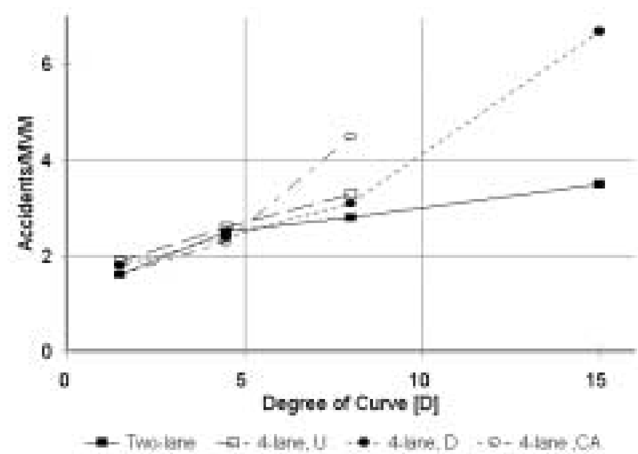


Figure 1. Accident rate versus degree of curve for four road types.

[1] Earlier drafts of this papers were prepared in the course of a project for UMA Engineering (for the new Canadian Geometric Design Guide) and for DELCAN (in ORSAM 98).

Second, Raff's data is the result of pooling from many states with differing accident reporting. As a result some of his conclusions are out of line with what later research has found.

1971. One of the early comprehensive reviews of empirical findings is by Leisch & Assoc. (1971). Figures 2 and 3 are based on the juxtaposition of five old studies. The same data points are used in both figures, except that one shows the degree of curve on the horizontal axis and the other shows the curve radius.

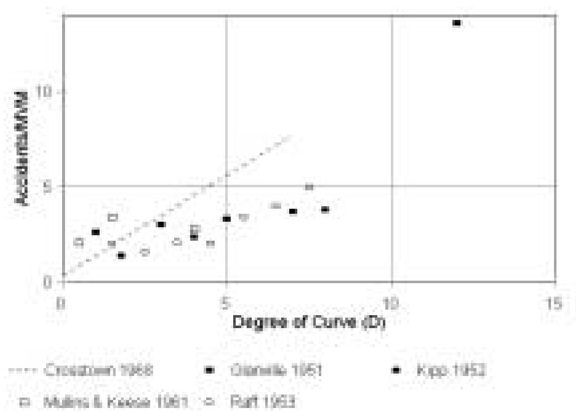


Figure 2. Five early studies.

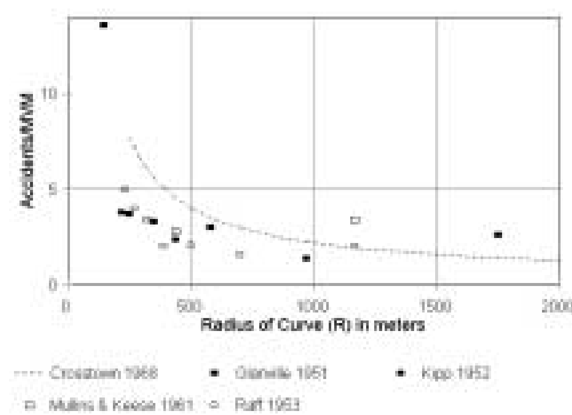


Figure 3. Data from Figure 2 shown against radius of curvature.

When accident rate is plotted against the degree of curve it seems obvious that decrease from 10° to 9° has approximately the same beneficial effect on accident rates as a decrease from 3° to 2°. However, when the accident rate is plotted against the radius it appears as if increasing the radius from 200 m to 300 m has a much larger beneficial effect on the accident rate than an increase from 900 m to 1000 m. This has been at times misinterpreted to mean that in the relationship there is some natural bend or 'knee' around R=500 m and therefore increasing the radius beyond, say, 500 m is unimportant. Obviously, whether there is such a 'knee' depends only on the axis chosen for the presentation, whether the vertical axis is R or D. Thus, there is no 'knee' in figure 2. However, since the decline in accident rate beyond $R \approx 500$ m is gradual, it is natural that such a decline in risk may escape statistical significance.

The data on which Figures 2 and 3 are based are for several road types. In spite of this, there seems to be a large measure of congruence in the empirical findings. An eyeball fit is: accidents/MVM= 1.8+0.34D.

Also from the review by Leisch & Assoc. (1971) is the information in Table 1. Here, curved freeway sections are seen to have a larger accident rate than tangent (straight) freeway sections.

Table 1. Mean accident rate in Chicago Expressways.*

	Accidents/MVM*
Level, Tangent	1.10
Level, Curved	2.29
Upgrade, Curved	2.25
Downgrade, Curved	2.56

MVM - million vehicle miles

1978. Additional information about the effect of curvature on controlled access highways comes from Dunlap et al. who used linear multivariate regression to examine how elements of horizontal and vertical alignment affect the accident rate on the Pennsylvania and Ohio Turnpikes. Their results for the effect of horizontal curvature are shown in Figure 3.

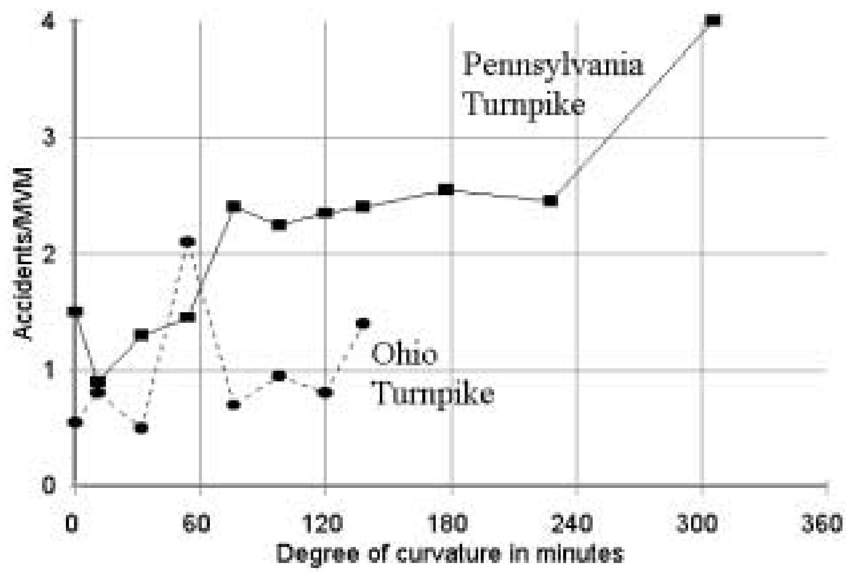


Figure 3. Accident rate versus degree of curve for two turnpikes.

The empirical relationships for the Pennsylvania Turnpikes in Figure 3 is quite clear and consistent with all earlier findings. However, the pattern for the Ohio turnpike is quite different. Thus, the clear association between degree of curve and accident rate is not always present.

1982 a. McBean studied the prevalence of selected geometric features at sites where an accident has occurred and nearby sites subject to the same traffic and other influences. There were 197 site-pairs. The main results are in Table 2.

Table 2. Number of accident and control sites by carriageway width.

	Radius	Accident sites					
		Straight	>3000 ft.	1500-3000 ft.	500-1500 ft.	<500 ft.	Total
Control sites	Straight	45	7	12	22	11	97
	>3000 ft.	4	1	6	14	0	25
	1500-3000 ft.	12	2	9	16	2	41
	500- 1500 ft.	6	4	1	16	3	30
	<500 ft.	1	0	0	3	0	4
	Totals	68	14	28	71	16	197

Were the radius unrelated to accident occurrence, one would expect the corresponding row and column sums to be approximately the same. However, we see that 16 accident sites but only 4 control sites had a radius below 500 ft. From this evidence (and the corresp onding statistical analysis) McBean concluded that there is a "strong indication that radius of curvature tends to be smaller at the accident sites than at the control sites. He then proceeded to search for that radius above which sites are equally likely to be in the 'accident' and the 'control' group. He finds this value to be approximately 1500 ft. This result is quite consistent with the representation in Figure 4. If accident frequency is proportional to degree of curve the relationship with radius describes a hyperbola which implies "a rapid increase of accident risk" (p.8) for short radii and a gradual decrease in accident risk for large radii.

1982 b. The results in Table 3 are reported in the Synthesis (1982) as taken from a report by Smith et al. (1981).

Table 3

Degree of curve D	Data base 1 Accidents/ MVM	Data base 2 Accidents/M VM
0	2.199	
0<D<1.55	2.252	
1.55<D<3.25	2.503	4.590
3.25<D<5.50	2.319	5.960
5.50<D		7.718

The two data bases were assembled by two different agencies and obviously show discrepant results. While in data base 1 there is no association between D and accident rate, it is clearly present in data base 2.

1982 c. Another confirmation of the relationship between accident rate and radius of curvature comes from a study by Matthews and Barnes in New Zealand. The data are for 4666 curves from State Highways 1 and five years of accidents (total of 1082). The authors find that (for injury accidents?):

$$Accidents/MVkm = 8.5/R^{0.64} = 0.071 \times D^{0.64} \qquad \textbf{(1)}$$

These relationship are shown in Figures 4 and 5.

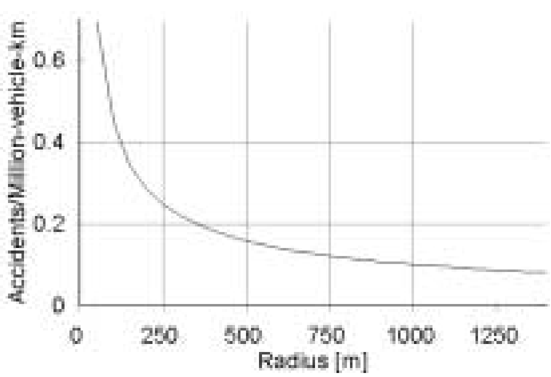


Figure 4.

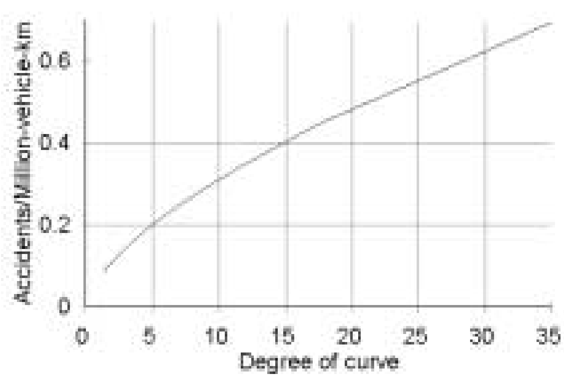


Figure 5.

1985. Glennon et al. collected data in four states about 3557 road segments of which 3304 contained a curve. Each 'curve segment' consisted of a curve and a minimum of 200 m of tangent at each end and was 1 km long.
In an overall linear regression relating accidents/MVM to various covariates, the following regression coefficients were found:

Table 4

Covariate	Regression Coefficient
Degree of curve	0.056
Length of curve [miles]	-0.141
Roadway width [ft.]	-0.023
Shoulder width [ft.]	-0.057

A discriminant analysis was performed with the intent to identify combinations of covariates that are associated with unusually many or few accidents. The results cannot be interpreted in termsd of Accident Modification Functions.

The authors conclude that: (1) Accident rates on curves are three times the average rate on tangents; (2) single vehicle RORA are the predominant type of accident on curves; (3) on wet or icy pavements the accident frequency is almost three times that on dry pavements; (4) road side, degree of curve, length of curve, shoulder width and pavement friction were all determinants of accident rate.

1986. Deacon reinterpreted data assembled by Glennon et al. (1985). The data consists of 351 straight and 3297 curved road segments. Each road segment was 1 km long. Curved road segments consisted of a curve and at least 200 m of tangent on each side. Table 5 summarizes some of the data.

Table 5

Degree of Curve	Accidents/MVM	ADT	Avg. Lane width [ft]	Avg. Shoulder width [ft]
0	.90	3400	11.5	7.2
0.01-0.74	1.38	3100	11.7	7.7
0.75-1.49	1.06	3300	11.9	7.5
1.50-2.49	1.24	3200	11.8	7.4
2.50-3.49	1.61	3400	11.7	7.3
3.50-4.49	2.41	3000	11.3	6.3
4.50-6.49	2.79	3200	10.9	5.9
6.50-8.49	2.89	3300	10.4	4.8
8.50-10.49	3.59	3000	10.2	4.8
10.50-12.49	4.03	3200	10.3	4.8
12.5 or more	4.19	2900	10	4.8

As is evident, the sharper curves tend to have narrower lanes and shoulders. One may surmise that the degree of curve is associated with other road features as well. Thus, e.g., one may expect long curves in level terrain to be associated with small degrees of curve and vice versa. Therefore, a part of the increase in accident rate that is evident in column 2 may reflect the influence of these correlated variables. After some data manipulation, Deacon (1986) suggests to use:

$$A=(r\times L+0.0336\times D)\times V \qquad \textbf{(2)}$$

In this, A is the number of curve accidents, r is the accident rate (accidents per million vehicle miles) on a straight road segment, L is curve length in miles, V is the number of vehicles (in millions), and D is the degree of curve.

Deacon arrived at this formulation because each curve in the Glennon et al. (1985) data-set was preceded by a straight section and the available accident count was joint for the straight and curved parts of the 1 km segments which served as data. However, no matter what its motivation, Deacon's model is conceptually different from all previous work. It implies that the increase in accidents on a curve (0.0336×D×V) is due to the mere existence of the curve of degree D, and does not depend how long the curve is. It is as if the curve was partly a 'point-risk' (akin to an intersection, narrow bridge, or a tree) so that if the driver manages the difficulty of changing from the straight to the curved section or changing back from the curve into the straight section, the rest of the journey along the curve is just like any straight road. If true, this has major implications on the meaning of all previous work. All previous research was done about the association of accidents/MVM to degree of curve. If Deacon is right, if a horizontal curve is partly a point-risk, then such an association would be found even if the degree of curve has nothing to do with the risk of accident occurrence.

To explain why, consider two curves, both used by 1 million vehicles/year. Curve A is a 1° curve that is 1 mile long; curve B is a 10° curve that is 0.2 miles long. Assume that the entry and exit of a curve, no matter what its degree causes 1 accident/mile of curve. If so, curve A will have 2 accidents/MVM and curve B will have 1.2/0.2=6 accidents/MVM. Thus, in this contrived example, the appearance that the higher degree curve B is associated with a larger risk is due to the simpl y curve B is shorter than curve A and therefore has fewer vehicle miles of travel. The moral of the example is that even if the hazard associated with the change from tangent to curve did not depend on D, short curves would appear to have a higher accident rate. Since curve with large D are naturally short, an appearance of risk being a function of D would necessarily follow. Thus, accidents/MVM is the incorrect vehicle for investigating the effect of D on safety. All inquiries that were conducted in terms of accidents/MVM are in danger of being severely biassed. What appeared in most previous research to be a clear association between degree of curve and accident rate is partly or mostly a reflection of the association between degree of curve and curve length.

1988. Another study is by Lamm et al.. Using data from 261 road sections (two-lane rural?) and 3 years of accident counts (815 accidents) in a multivariate linear regression the authors find that:

$$Accidents/MVM = -0.88 + 1.41D \;\; for \;\; 1° < D < 6.9° \qquad \textbf{(3)}$$

The authors note that the "degree of curve was found to be the best single variable predictor available. The other variables helped the regression model but the equation did very well even without them." (p. 9)

1990. Hedman using a graph from Brüde (1976) shows a graph in which the accident rate index declines sharply with radius of curvature in a hyperbolic fashion up to a radius of about 1000 m and continues to decline mildly up to radii larger than 3000 m. There is a hint in the graph that for a straight section that accident rate index is larger than for roads with a long radius.

1991, 1992. A major research effort was conducted by Zegeer et al. (1991, 1992 b). The data base consisted of 10,900 horizontal curves in Washington State with traffic, accident and geometric characteristics of each curve. After analysis the following model was adopted:

$$A = (1.552L + 0.014D - 0.012S) \times V \times 0.978^{W-30} \quad \textbf{(4)}$$

In equation 4, A is the number of accidents/year; L is length of curve in miles; D is degree of curve; S=1 if spirals exist and 0 otherwise; V is volume of vehicles/year in millions (both directions); W is 'roadway width in feet' - the total width of lanes+shoulders.

The functional form of equation 4 is the same as Deacon's and has been adopted not so much because it fits the data best, but mainly because "the interaction of traffic and roadway variables are reasonable and make sense in terms of accident occurrence on curves."(p.14). To interpret equation 4, the magnitude of its components is given in Table 6 for a few values of D and L (using ADT=3000 or $V=3000\times365/10^6$ and W=32 ft.).

Table 6

1 Degree of curve	2 Curve length [miles]	3 Line accidents 1.552×L×V	4 Entry (Exit) accidents 0.014×D×V	5 Spiral reduction 0.012×S×V	6 Road Width Multiplier 0.978^{W-30}	7 Accidents/ year
1°	1.00	1.699	0.015	0.013	0.956	1.63
1°	0.50	0.850	0.015	0.013	0.956	0.81
10°	0.20	0.340	0.15	0.013	0.956	0.46
10°	0.10	0.170	0.15	0.013	0.956	0.30

Column 3 gives estimates of the number of accidents associated with the *passage* of the curve. This number does not depend on the degree of the curve, only on its length. In fact, Zegeer et al. use this expression to estimate the number of accidents on straight road sections (tangents). This implies that (according to this model) once a driver successfully negotiates the entry into or exit from a curve, the chance of an accident along a sharp curve, a mild curve, or a straight section is just the same.

Column 4 gives estimates of the number accidents associated with the difficulties arising near the *entry to or exit from* the curve. This is the only term in equation 2 that varies with degree of curve. Comparison to column 3 shows that this term is of importance mainly for short curves and relatively high degrees of curve.

Column 5 shows the accident reduction due to the presence of a spiral. In the model it is a constant that almost negates the harm of a 1° curve but is relatively unimportant when compared to the harm of a 10° curve. Column 6 is an indication of the effect of roadway width. Here the width of the two lanes + shoulders is 32 feet. The excess above 30 feet is seen to reduce total accidents by 4.4%.

Several questions may now be asked. Is it really so that once the entry or exit are negotiated safely, the passage along a sharp curve is just as hazardous as along a straight road? I do not know of research that answered this question. F. Council tells that manual examination of police accident records led him to believe that 40%-60% of curve accidents occur near the curve entry or exit. One can also ask whether it is true that the benefit of the presence of a spiral is constant and does not vary with degree of curve or with spiral length?

It is possible to attempt an answer to such questions by postulating alternative model forms, estimating parameters and examining model residuals. Thus, e.g., keeping close to the structure of equation 2 one could have estimated the parameters of a model $A=[f_1(D)\times L+f_2(D)+f_3(D)\times S]\times V\times f_4(W,D)$ in which the f's are various functions. Since this has not been done, since the form of equation 2 has been postulated for reasons of logical appeal, we cannot yet take equation 2 as an indication that indeed curve accidents can be separated in 'entry or exit' and 'line' accidents. Nor can one take it as having demonstrated that 'line' accidents are independent of curvature.

1995 a Miaou used data from Utah for 11539 two-lane rural undivided road sections and 6680 single vehicle accidents for eight years to estimate a multivariate model. The regression parameters were: $\beta_{\text{all road}}=-0.0367$, $\beta_{\text{speed limit-55 mph}}=0.0844$, $\beta_{\text{speed limit<55 mph}}=0.0246$.

1995 b. Voigt used data from 247 curves on two-lane rural roads in Texas and seven years of accident data and estimated that:

$$\text{Accidents/MVM}=0.102\times e^{0.064D}-0.1$$

This relationship is shown in Figures 6 and 7.

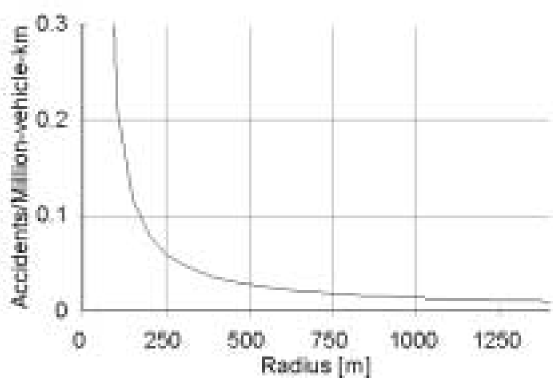


Figure 6.

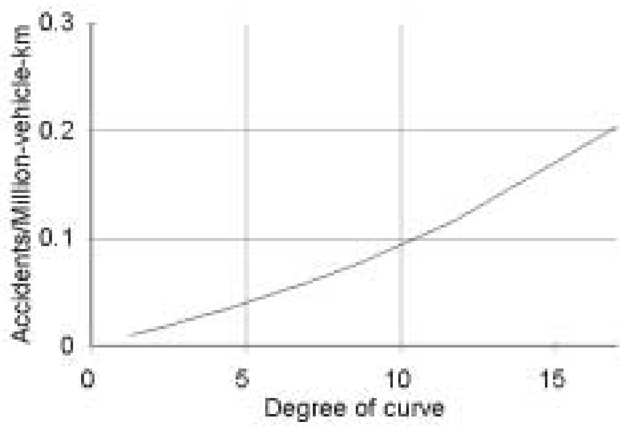


Figure 7

1996. Hanley et al. report on before-after studies from California sites where curve radii were increased. The results are in Table7.

Table 7

Treatment	Before Accidents	After Accidents	Comparison Ratio	AMF without RTM Correction	AMF with RTM Correction
Radius increase+ Shoulder and Lane widening	13	10	1979/2313	0.90	0.96
Radius increase+shoulder widening	50	36	323/383	0.85	0.86
Radius increase	22	20	1656/1930	0.94	0.92

Since it is not known what the radii before and after the treatment were the results can not be translated into information that is useful in a design context. It is not clear from the report whether equal lengths of road are being compared.

1999. Most research showed that the relationship between the accident rate 'r' and D is of the linear form

$$r = r_0 + \alpha D \qquad \textbf{(4)}$$

where r_0 is the accident rate on tangents. Hauer shows that equation 1 implies that if a short sharp curve is replaced by a longer and less sharp curve, the difference in the number of accidents is the product: (difference in the length of the two curves)×(accident rate on a tangent), irrespective of whether α in equation 4 is positive, negative or zero.

Hauer finds that if the Deacon-Zegeer assumption is right, when a curve of degree D_1 is replaced by a less sharp curve of degree D_2 then the annual reduction in accidents is:

$$AnnualAccidentSavings = V[r_0(\frac{1}{D_1} - \frac{1}{D_2})(2\tan\frac{I}{2} - I) + 0.014(D_2 - D_1)] \quad \textbf{(5)}$$

where V=million of vehicle/year (both directions),

r_0 =the accident rate on a straight section of that road.

I= deflection angle.

If the model in equation 4 is right that the last term in equation 5 needs to be omitted.

Summary.

The empirical evidence seems to indicate that:

- In several studies, the accident rate increases approximately linearly with degree of curve. Because the radius is proportional to the reciprocal value of the degree of curve, the accident rate diminishes approximately hyperbolically with curve radius.

- The tendency of the accident rate to increase as the degree of curve increases is present not only on two-lane rural road but also on multilane roads and access controlled roads in urban and rural environments.

- There are a few studies that did not find the tendency for accident rates to increase with degree of curve and in some studies the increase was not linear.

- The habit researchers to relate the degree of curve to accident rate (accidents/MVM) leads to an ambiguity. Because sharp curves tend to be also short, after all the research done so far we still do not know whether when moving along a curved path the chance of an accident increases with the degree of the curve or whether the entry and exit to a curve are 'point risks' with an elevated chance of accident that is a function of the degree of curve, or whether the truth is a mixture of both.

5.2. External factor: Tangent length.

The radius or degree of curve is a trait of a specific curve has been seen to influence the number of accidents on it - it is a factor 'internal' to the curve. But accident occurrence on a curve is believed to be also a function of the speed, attitudes and expectations with which road users approach the curve. These are fashioned by what the road users have experienced before reaching the specific curve. Such speed, attitude and expectations may depends on variables such as 'the length of the preceding tangent' or the 'preceding curve density'- these are 'external factors'.

1946. One early piece of empirical evidence about the importance of an external factor comes from Baldwin and is shown in figure 8.

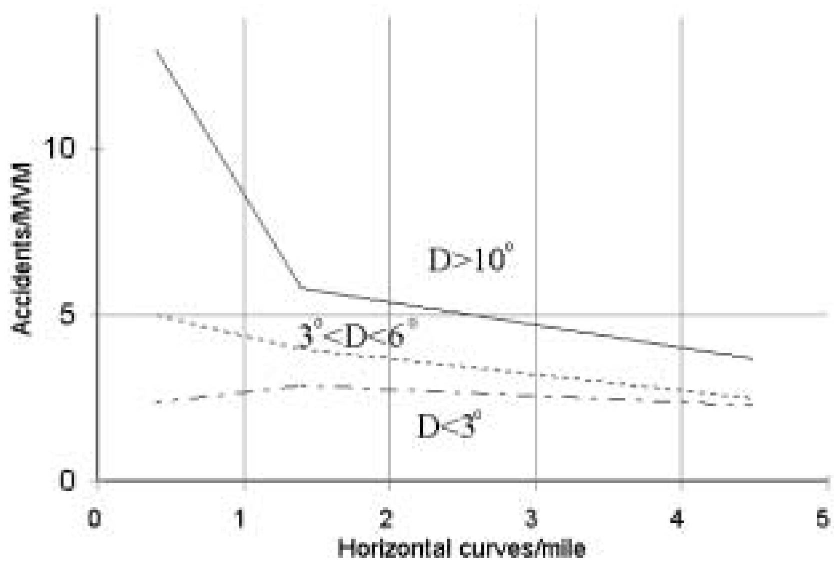


Figure 8. The influence of curve density.

The horizontal axis gives an indication of the average length of straight sections (tangents) that precede curves. Evidently, long tangents before sharp curves have a large influence on the accident rate whereas when there are perhaps 2 curves per mile, the influence of the length of the tangent is relatively small..

1965. Figure 9 is based on a British study showing that the accident rate at small radius curves is very high when the average curvature of the entire alignment is small. Average curvature is defined as the sum of deflection angles divided by road length. Curves with a radius of less than 1000 ft. if located on a road with low average curvature seem to have a very large accident rate. This finding is based on a total of 731 injury accidents of which only 18 are in the 20°/mile curvature-<1K ft. radius group.

1988. Perhaps the clearest empirical evidence comes from all curves on the 2000 km long New Zealand State Highway 1 reported by Matthews and Barnes who give the following data in their Table V shown here as Table 8.

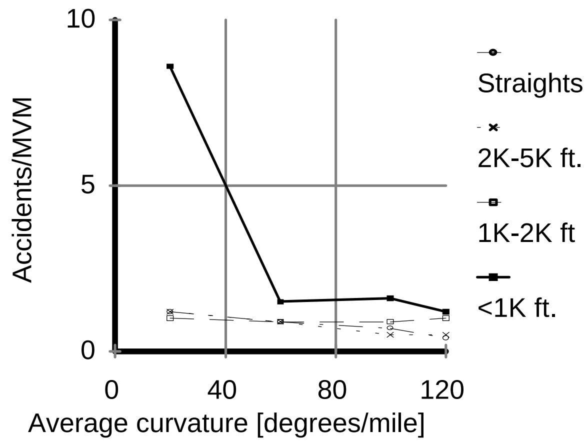


Figure 9

Table 8. Accidents rates (acc./10^6 vehicle-kilometres) as radius and tangent vary.

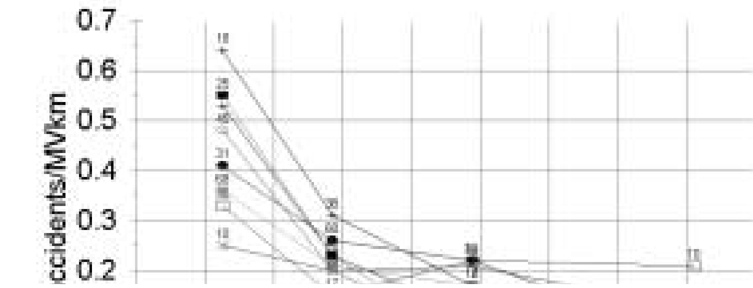
Radius [m]	Tangent length [m]							
	25	75	125	175	300	500	800	1200
126	0.33	0.36	0.48	0.41	0.53	0.25	0.55	0.64
286	0.15	0.21	0.2	0.26	0.23	0.2	0.23	0.31
489	0.22	0.17	0.07	0.22	0.11	0.21	0.05	0.17
812	0.21	0.07	0.12	0.06	0.15	0.12	0.08	0.1

To give an impression of the precision of these rates, Table 9 shows the accident counts from which rates were calculated.

Table 9. Accident counts.

Mean Radius [m]	Mean Tangent Length [m]							
	25	75	125	175	300	500	800	1200
126	50	68	45	31	72	10	25	18
286	17	67	51	68	112	55	43	38
489	13	10	8	36	40	30	13	17
812	10	11	13	10	45	22	20	17

The accidents rates of Table 8 show certain regularities which are evident in Figures 10 and 11.



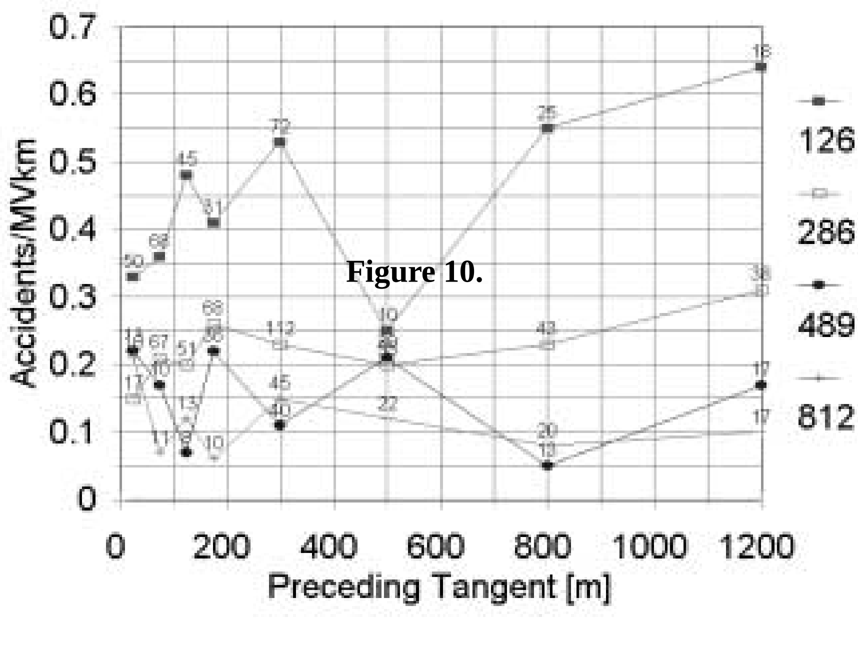


Figure 10.

Figure 11.

After some fiddling I eyeballed the following function to the data:

$$AR = \begin{cases} \exp(1.73\times10^{-6}R^2 - 4.17\times10^{-3}R)\times\exp[-(6.2\times10^{-4} - 1.2\times10^{-6}R)\times(1200-T)] \;\; if \;\; R<500m,\; T<1200\,m \\ \exp(1.73\times10^{-6}R^2 - 4.17\times10^{-3}R) \;\; if \;\; R>500m. \end{cases} \qquad \textbf{(6)}$$

in which
AR is the accident rate in accidents/10^6 vehicle kilometres,
R is the radius in metres,
T is the length of the tangent in metres.

The fitted values for cells corresponding to the data in Table 6 are given in Table 10.

Table 10. Fitted values.

Radius	Tangent							
	25	75	125	175	300	500	800	1200
126	0.35	0.36	0.37	0.38	0.40	0.44	0.50	0.61
286	0.25	0.26	0.26	0.26	0.27	0.29	0.31	0.35
489	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.20
812	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

The fitted equation implies that for curves with R>500 m (irrespective of T) and for curves with T>1200 m, the accident rate does not depend on T. For other curves, that is for curves with R<500 m and T<1200 m, there is an accident modification factor:

$$AMF = \exp[-(6.2\times10^{-4} - 1.2\times10^{-6}R)\times(1200-T)] \qquad \textbf{(7)}$$

This AMF is in Table 11.

Thus, e.g., if the 250 m radius horizontal curve is preceded by a 400 m tangent it will have

Table 11. AMFs for tangent length.

	T[m]														
R[m]	50	100	150	200	250	300	400	500	600	700	800	900	1000	1100	1200
50	0.53	0.54	0.56	0.57	0.59	0.60	0.64	0.68	0.71	0.76	0.80	0.85	0.89	0.95	1.00
100	0.56	0.58	0.59	0.61	0.62	0.64	0.67	0.70	0.74	0.78	0.82	0.86	0.90	0.95	1.00
150	0.60	0.62	0.63	0.64	0.66	0.67	0.70	0.73	0.77	0.80	0.84	0.88	0.92	0.96	1.00
200	0.65	0.66	0.67	0.68	0.70	0.71	0.74	0.77	0.80	0.83	0.86	0.89	0.93	0.96	1.00
250	0.69	0.70	0.71	0.73	0.74	0.75	0.77	0.80	0.83	0.85	0.88	0.91	0.94	0.97	1.00
300	0.74	0.75	0.76	0.77	0.78	0.79	0.81	0.83	0.86	0.88	0.90	0.92	0.95	0.97	1.00
350	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.87	0.89	0.90	0.92	0.94	0.96	0.98	1.00
400	0.85	0.86	0.86	0.87	0.88	0.88	0.89	0.91	0.92	0.93	0.95	0.96	0.97	0.99	1.00
450	0.91	0.92	0.92	0.92	0.93	0.93	0.94	0.95	0.95	0.96	0.97	0.98	0.98	0.99	1.00
500	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00

0.77×number of accidents of a 250 m radius curve preceded by a very long tangent (longer than 1200 m).

1993. Brenac (1996) provides a summary of international experience. He mentions a French study (Renault et al., 1993) which, using Poisson regression techniques shows that the accident rate on curves increases when the radius decreases and the length of straight alignment preceding the curve increases. These statistical findings are supported by other studies which examine circumstances the generate high accident rates and loss of control accidents.

1995. Fink and Krammes in their literature review speak of mixed results. A 1983 study by Datta et al. found tangent length to be a significant predictor of accidents while Terhune and Parker (1986) concluded that tangent length was not a significant variable. Zegeer et al. (1991) are said to hav e observed that "there appears to be evidence that tangents above a certain length may result in some increase in accidents on the curve ahead'. In examining their own data (563 curves from New York, Washington and Texas) Fink and Krammes conclude that: "First, the results support the hypothesis that the (detrimental safety) effect of longer approach tangents becomes more pronounced at higher degrees of curvature. Second, the results do not support the hypothesis that short tangent length s increase safety problems."

Summary.

- The weight of empirical evidence is that when a long tangent is followed by a sharp curve, the number of accidents is elevated. This conclusion is in line with what we know about driver behaviour in speed choice and the likelihood of driver error when encountering the unexpected. The AMF in equation 7 seems to capture this phenomenon.

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5.1 Horizontal Curve Radius or Degree.

Author, Year.	Method	Size	Accident modification functions	Acc./ type	Conf. rating	Conditions	Comments
Raff, 1953	C/S Uni-variate	5000 miles, 15 States	Accidents/MVM=1.3+0.25D AMF(Δ°)=1+0.25×Δ/(accid./ MVM before). Applies to accid./MVM Ex.: Δ=-2.1°, 3 accid./MVM; AMF=1-0.175=0.825	All	0.5	Messy data, pooled under different reporting conditions	Single covariate tabulation. Confounded by covariation with other factors.
Leisch & Ass., 1971	C/S Uni-variate	Compilation of 5 studies	Accidents/MVM=1.8+0.34D AMF(Δ°)=1+0.34×Δ/(accid./ MVM before). Applies to accid./MVM Ex.: Δ=-2.1°, 3 accid./MVM; AMF=1-0.238=0.762	All	0.5	Disparate studies pooled.	Single covariate tabulation. Confounded by covariation with other factors
Dunlap et al., 1978	C/S Linear Regression	5533 Ohio 9822 Penn	Increasing accident rate with D for Penn., no increase in Ohio	All, single, wet	2	Pennsylvania and Ohio Turnpikes	8 curvature categories from 0 to about 2.5°. All accident types have same relationship

Author, Year.	Method	Size	Accident modification functions	Acc./ type	Conf. rating	Conditions	Comments
Smith et al., 1981	C/S, simple	2 data bases assembled for a different purpose	In data-base one accident rate does not increase with D, in the other data base it increases steeply			No detail available	
McBean, 1982	Case-Control	197 matched site-pairs	Accident sites have smaller radius than non-accident sites. No AMF can be extracted	Injury	2	Compares sites where there was an accident to nearby sites upstream	
Mat-thews &Barnes, 1982	C/S Simple	1082 accidents on 4666 curves	Accidents/MVkm=$0.071D^{0.64}$	Injury	1.5	New Zealand, State Highway 1	

Glennon et al., 1985	C/S multiva-riate & discri-minant	3304 curve seg-ments, 13545 accid., 3 years	$AMF(\Delta_D)=1+0.056\Delta_D/f(\underline{X})-0.141\times(1.09I/D^2)\times\Delta_D/f(\underline{X})$ in which D is degree of curve, $f(\underline{X})$ is the curve accident rate in accid/MVM, I is the central angle in radians. D=1.09/R in miles, L=1.09I/D in miles.	Total acci-dent rate	1.5	Data from Florida, Ill, Ohio, Texas By road width, curve length & radius, ADT	The multivariate regression part is done without much attention. As a result, AMF not reliable.
Deacon, 1986	Uses data from Glennon et al.	3304 curve seg-ments, 13545 accid., 3 years	A=(rL+0.336D)V A=number of curve accidents r=accid./MVM on tangent L= curve length (miles) V= vehicles in miilions $(1.09\times AR\times I/D_{small}+0.0336D_{small})/(1.09\times AR\times I/D_{small}+0.0336D_{large})$ AR accid./MVM on tangent, I central angle in radians.	Total accid.	2	Reinterprets Glennon's data.	Views curve as point risk+length.
Author, Year.	**Method**	**Size**	**Accident modification functions**	**Acc./ type**	**Conf. rating**	**Conditions**	**Comments**
Lamm, 1988	C/S, Linear regressi on	261 road sections, 815 accident	Accidents/MVM=-0.88+1.41D when $1°<D<6.9°$	Total	1.5	Each site was a sequence of tanget-curve-tangent	

Hedman, 1990	C/S	Based on study by Brude	Accident rate index declines with radius in hyperbolic fashion	?	?	?	?
Zegeer et al., 1992	C/S multiva -riate,	10,900 horizontal curves, 12123 acc. In 5 years	AMFs are function of central angle I, Original (D_o) and New (D_n) degree of curvature. E.g., I=20°, D_o=30° and D_n=15°, AMF=0.50-0.52. *$1+0.014\Delta D/[1.55(L-(L/D)\Delta D)+0.014D-0.012S]$* (?) D-degree of curve, L-length in miles, S-1 if spiral present.	All acci- dents	2	Two-lane rural highways, Washington	Accidents are assumed proportional to AADT. If this is not true, and when D and AADT are correlated, the result will be biassed.
Li et al., 1994	C/S Multiva riate	163 sections 560 km	$AMF(\Delta_D)=1+(0.0024\sqrt{\text{private access/km}}+0.0030\sqrt{\text{roadside pullouts/km}})\Delta_D/\sqrt{\text{Accid/km}}$	All & Fat+Inj	2		Model equation includes ADT in additive form. This is illogical.
Voigt, 1995	C/S	247 curves, 7 years of accidents	Accidents/MVM=$0.102e^{0.064D}-0.1$	All	1.5	Two-lane rural; roads in Texas	
Author, Year.	Method	Size	Accident modification functions	Acc./ type	Conf. rating	Conditions	Comments

Miaou, 1995	C/S Multi-variate	11539 road sections. 1985-92 Utah 6680 SV.		0.963±0.003 for 1 degree	All roads	.Single veh. off-the road	2	mainly rural two-lane but including HPMS 2,6,7,8,9 Non-intersection	Lane width is not included in variables. Section length is variable with negative coefficient
				0.916±0.005 for 1 degree	Speed limit=55 mph				
				976±0.005 for 1 degree	Speed limit<55 mph				
Hanley et al. 1996	B/A Emp. Bayes	acc Bef	Acc Aft	Treatment	AMF	All	1	Supereleva-tion and curve corrections. Small sample sizes.	Even though the standard errors are large, taken together the results seem to indicate small accident reductions.
		13	10	Rad.&Shldr+ Lane.widen	0.96±0.40				
		50	36	Rad.&Shldr.	86%±.50				
		22	20	Radius only	0.92%±0.30				
Hauer, 1999	Analy-sis	Zegeer& Deacon data		Annual accident savings= $V[r_0(1/D_1-1/D_2)(2\tan(I/2)-I)+0.014(D_2-D_1)]$ where V=million vehicles/year r_0=accident rate on tangent I deflection angle		All			