Safety Aspects of Individual Design Elements and Their Interactions on Two-Lane Highways: International Perspective

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The results of an extensive literature review of the safety performances of low- and intermediate-traffic-volume, two-lane rural highways are presented. The effects on traffic safety, as measured by accident rates, of pavement width, radius of curve/degree of curve, gradient, sight distance, traffic volume, and design speed on curved sections of two-lane rural highways are covered. The following are some of the main findings. There is a distinct tendency for accidents to decrease with increasing pavement width up to about 7.5 m (25 ft). There exists a negative relationship between radius of curve and accident rate. The sharper the radius of curve, the higher the number of run-off-the-road accidents. Curves that dictate a significant change in operating speeds and that cause nonhomogeneity in road characteristics are especially dangerous. The most successful parameter in explaining the variability in accident rates was degree of curve (United States) or curvature change rate (Europe). Gradients of up to about 6 percent have a relatively small effect on the accident rate. A sharp increase in the accident rate was noted on grades of more than 6 percent. There exists a negative relationship between available sight distance and accident risk. However, other influencing parameters, such as wide pavements and gentle radii of curve, might also play a part in the observed positive effect of sufficient sight distances on the accident situation. For narrow road sections, an increase in sight distance could favorably affect traffic safety. A negative relationship between traffic volume and road traffic accidents was established. Run-off-the-road accidents were found to decrease with increasing average annual daily traffic up to 10,000 vehicles per day. Recent investigations reported a U-shaped distribution between accident rate and traffic volume. An accident rate of 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi) was proposed as a breakpoint between levels of safety and unsafety. This breakpoint was derived from relationships between single design parameters and accident rate as well as from the superimposition of the design parameters. Limiting values for a number of design parameters are also proposed. If these limiting values were exceeded, the proposed breakpoint, in relation to the accident rate, would be exceeded.

"Two-lane rural highway safety is an issue of pressing national concern. It has been identified as the highest priority research need by the Transportation Research Board's Committee on Geometric Design (A2A02)" (*1*).

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The approximately 5.0 million km (3.1 million mi) of two-lane rural highways in the United States represents 97 percent of rural mileage and 80 percent of all U.S. highway miles. Two-lane rural highway travel constitutes an estimated 66 percent of rural highway travel and 30 percent of all U.S. highway travel. Two-lane rural highways have (*2*)

- Higher accident rates than all other kinds of rural highways except four-lane undivided roads.
- Higher percentages of head-on collisions than any other kind of rural highways and also higher percentages of single-vehicle accidents.

The probability of an accident on two-lane rural highways is highest at horizontal curves, intersections, and bridges (*2*).

Many factors may exhibit a measurable influence on driving behavior and traffic safety on two-lane rural highways. These include, but are not limited to,

1. Human factors, such as improper judgment of the road ahead and traffic, speeding, driving under the influence of alcohol or drugs, driving inexperience (young people), handicaps (especially for the older segment of the driving population), and sex (*3,4*).
2. Physical features of the site, such as horizontal and vertical alignments, and cross section combined with the degree of roadside development and access control.
3. Presence and action of traffic, such as traffic volume, traffic mix, and seasonal and daily variations.
4. Legal issues, such as overall mandatory federal and state laws, type of traffic control devices at the sites, and degree of enforcement.
5. Environmental factors, such as weather and pavement conditions.
6. Vehicle deficiencies, such as tires, brakes, and vehicle age.

All of the above therefore constitute a complex mix of various causes of traffic accidents, of which the road itself represents only one factor, but a very important one.

To show to what extent safety in traffic is influenced by the road itself, the first step would be to select those elements that may well characterize the latter. These include, most important, the design parameters, the cross section, and traffic volume, since they can easily be evaluated in terms of size and number. However, these parameters affect the accident situation collectively rather than independently. Therefore, if conclusions were to be made about the design and traffic conditions of the road with regard to traffic safety, it is necessary to consider these interdependencies. Investigations into the relationship between one or a combination of design and traffic volume parameters and the accident situation may give valuable results, as long as it is understood that these parameters are among a variety of influencing factors that are related.

Numerous quantitative and qualitative analyses, appraisals, and discussions of traffic safety have appeared in the literature of highway and traffic engineering to provide a better understanding of accident risk characteristics. In the planning, design, and operation of a highway transportation system, knowledge of such characteristics is imperative if sound engineering decisions are to be made (*5–8*).

In this paper an extensive international literature review, coupled with the results of research studies by the authors, was conducted to provide current information on the safety performance of two-lane rural highways. The study covered the effects on traffic safety, as measured by accident rates, of pavement width, radius of curve/degree of curve, gradient, sight distance, traffic volume, and design speed on two-lane rural highways. These geometric design parameters were chosen for analysis because

1. It was anticipated that they would exhibit a measurable influence,
2. They can easily be measured, and
3. Accident research studies found statistically measurable impacts of these parameters on traffic safety.

It should be noted that this review may not be totally comprehensive and complete. For instance, the authors would have liked to learn more about the sample sizes and statistical techniques used in the various research studies to give some valuable comments on the papers investigated or to evaluate the worth of the reviewed studies. Unfortunately this information was not available or was incomplete in many publications. It appears that until the 1970s there was a tendency to report only the results of research studies without sufficiently describing the data bases or the analysis techniques used. Today, a research paper that does not give information on exact sample sizes and the analysis techniques used is not likely to be accepted by the research community. For these reasons, the reader should understand that the aim of the paper is, to a certain extent, informative rather than critical.

BACKGROUND

By and large, most geometric design guidelines are based on driving dynamic considerations. For example, some European guidelines (*9–12*) regard design speed as a driving dynamic safety parameter and attempt to tune design speed with actual operating speed as an indirect safety criterion to provide safe and gentle curvilinear alignments.

Geometric design guidelines have long been the subject of dispute. Some argue that the guidelines do not present a clear measure for evaluating the safety level of roadways. For instance, in their discussion of the German design guidelines, Feuchtinger and Christoffers (*13*) stated, "When a road goes into operation, the accident experience afterwards is the only indicator of the safety performance of the road. During the planning stage, there is no way to tell what level there is for traffic safety." Similarly, Bitzl (*14*) stated, "Unlike other engineering fields, in road design it is almost impossible to determine the safety level of a road. In other words, the guidelines provide no basic values to describe the safety level of a road, in relation to design parameters and traffic conditions; whereas in other engineering fields, such as structural, there exist safety values for constructing, for example, bridges or buildings." Similar statements about safety levels in highway geometric design guidelines were made by Auberlen (*15*) and Krebs (*16*).

In a discussion of the German design guidelines (*9*), Krebs and Kloeckner (*8*) said,

> • If the guidelines guarantee the safety of a road, then "no" or "only few" accidents should occur on that road. When accidents happen, drivers are always the ones who take the blame for the mishap.
>
> • Accidents are not uniformly distributed on the road network. High accident locations are clear indication that, besides driver's error, there exist other influencing parameters which are characterized by the road itself. (*8*)

Along the same line, Mackenrot stated the following in a previous publication (*17*):

> • No one is in a position to state whether a driver's discipline was in order before a high accident location, but then failed at that location. When a driver fails at a high accident location, it is often said that it was his way of driving which caused the accident.
>
> • When a driver fails a number of times at certain locations, then it becomes obvious that the problem lies, not with the driver, but mainly with the geometry of the road itself. (*17*)

The above statements indicate that no one is in a position to state whether a road section of considerable length is safe or not, nor can anyone guarantee that a road section will provide a minimum level of safety or a maximum level of endangerment, that is, unsafety.

INFLUENCE OF SINGLE DESIGN PARAMETERS

Pavement Width

Figure 1(*a*) depicts the relationship between accident rate and pavement width as derived from the results of several research studies.

Research studies have generally shown that adequate pavement widths are necessary for safe driving operation. The necessary widths are generally the result of the dimension of design vehicles and lateral clearances for transportation and safety maneuvers. If these widths are not sufficiently designed, impairment of traffic safety can originate. Therefore, it can be expected that there exists a certain correlation between pavement width and traffic safety.

Baldwin (*18*) investigated accidents on rural two-lane highways in the United States. He indicated that the accident rate decreases as pavement width increases. On the basis of his study, it appears that

1. Pavement widths of less than 5.5 m (18 ft) create unfavorable conditions for traffic safety.
2. The gain in safety is relatively small for pavement widths greater than 7 m (23 ft).

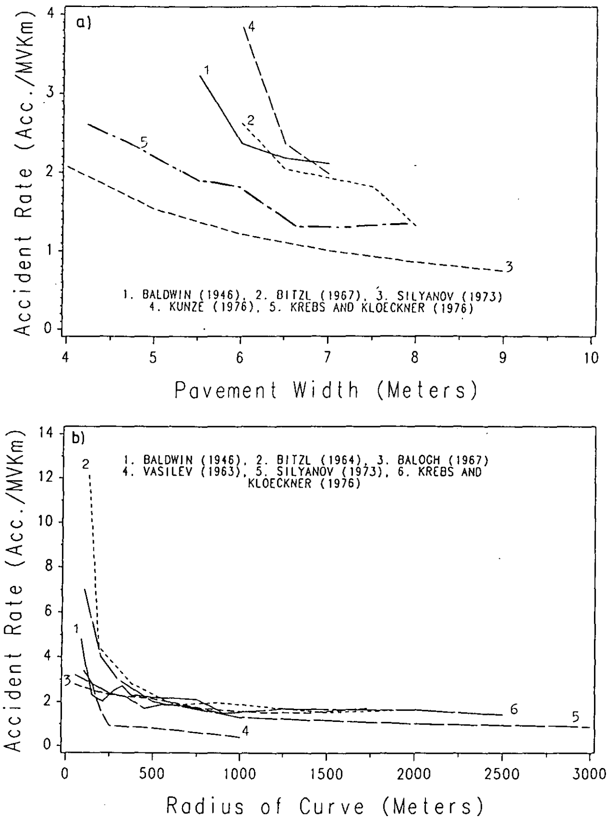


FIGURE 1 Examples illustrating the relationship between accident rate [number of accidents per 10^6 vehicle kilometers (Acc./MVkm)] and (*a*) pavement width and (*b*) radius of curve.

Cope (*19*) studied the effect of lane widening on accident rates on two-lane roadways in Illinois. He investigated 22 sections with an overall length of about 395 km (246 mi) whose pavements were widened from 5.5 m (18 ft) to 6.7 m (22 ft). The results of investigations done before and after the widening showed that the increase in pavement width reduced the accident rate from 1.4 to 0.9 accidents per 10^6 vehicle km (2.3 to 1.4 accidents per 10^6 vehicle mi). He also reported that the largest decrease in accident rate was on sections that had a high accident rate in the investigation done before the widening.

Bitzl (*20*) found a marked negative relationship between accident rate and pavement width in the Federal Republic of Germany (FRG). In several of his later investigations, Bitzl confirmed this result. For instance, in 1967 he stated the following: "Such a relationship is understandable since, if wider lane widths were available, overtaking or passing maneuvers could be accomplished with greater ease and smaller degree of danger" (*21*).

An investigation done by Winch (*22*) in Canada indicated that an increase in lane width leads to a decrease in accident frequency on two-lane rural roads. Similar conclusions were reported by Balogh (*23*) for Hungarian roads.

A comprehensive evaluation of international results by Silyanov in the former USSR (*24*) revealed that the accident rate decreases as pavement width increases for pavement widths of between 4 m (13 ft) and 9 m (30 ft). On wide pavements, he indicated that the accident rate decreases at a much slower pace than on narrower pavements.

A study cited by Pignataro (*25*) showed that the total accident rate per 10^6 vehicle mile decreased from 5.5 to 2.4 as the pavement width increased from 5 m (16 ft) to 7.5 m (25 ft). Another study, also cited by Pignataro (*25*), covering about 385 km (240 mi) of highways that had been widened from 5.5 m (18 ft) to 6.7 m (22 ft), indicated that the accident rate reduction ranged from 21.5 percent for low-volume roads to 46.6 percent for high-volume roads.

Kunze (*26*) studied the relationship between accident rate and pavement width classes in the FRG. He established a clear tendency for the accident rate to decrease with increasing pavement width classes for all accidents: run-off-the-road accidents, accidents at intersections, and head-on and rear-end accidents. Krebs and Kloeckner (*8*) established a negative linear relationship between pavement width and accident risk on two-lane rural highways. Zegeer et al. (*27*) reported that the accident rate in the United States decreases as pavement width increases up to about 7.25 m (24 ft).

A study by McCarthy et al. (*28*) on the effects of widening of lanes at 17 sites, in which the lanes were widened from 2.7 and 3.0 m (9 and 10 ft) to 3.4 and 3.7 m (11 and 12 ft), showed that a lane width increase reduced the injury-fatality accident rate significantly (22 percent) and caused a decrease in the total accident rate.

In addition to pavement width, Cirillo and Council (*29*) reported the following about shoulder width in the United States: "Most studies agree that shoulders up to 1.8 m (6 ft) wide on facilities with greater than 1000 ADT provide a safety benefit. The effect beyond 1.8 m (6 ft) is not clear."

Choueiri (*5*) and Lamm and Choueiri (*6,7*), who studied the joint impact of several parameters—degree of curve, length of curve, superelevation rate, gradient up to 5 percent, sight distance, lane width, shoulder width, and average annual daily traffic (AADT)—on accident rates on 261 two-lane curved sections in New York State, established a marginal negative relationship between pavement width and accident rate. The pavement widths considered in their study were 6.1 m (20 ft), 6.7 m (22 ft), and 7.3 m (24 ft). Shoulder width did not have a significant effect on the accident rate.

Statistical analyses by Zegeer et al. (*30*) of accident relationships based on an analysis of 10,900 horizontal curves on two-lane rural highways in Washington State with corresponding accident (12,123 accidents), geometric, traffic, and roadway data variables determined a 21 percent accident rate reduction for 1.2 m (4 ft) of lane widening.

The research studies reported above have generally shown that accident rates decrease with an increase in pavement width of up to about 7.5 m (25 ft) on two-lane rural roads. This increase in traffic safety was evident for all classes of radii of curves, gradients, and traffic volumes.

An extensive before-and-after investigation (*31*) covering 3 years of accident experience (1,428 accidents) on 28 sections with a section length of about 90 km (55 mi) redesigned according to the German design guidelines (*9*) established the results given in Figure 2 between the accident rate-accident cost rate and the pavement width. The regression curves in Figure 2 are based on the vehicle mileage calculated for every pavement width class. The relationship between accident rate and pavement width is in agreement with prior research; that is, the risk of being involved in an accident decreases as pavement width increases.

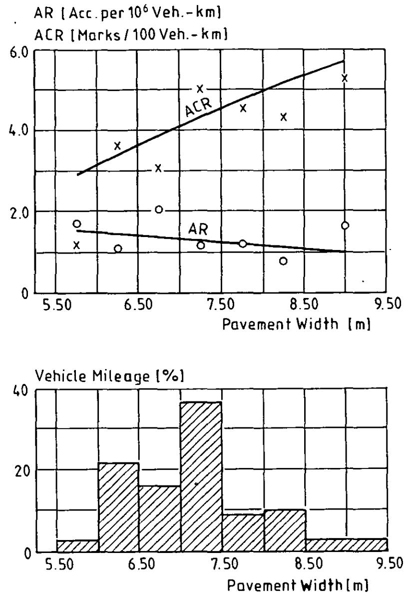


FIGURE 2 Accident rate (AR, in number of accidents per 10^6 vehicle kilometers) and accident cost rate (ACR, in Deutschmarks per 10^2 vehicle kilometers, where 1 DM ≃ $0.60, in 1994) versus pavement width.

Contrary to the opinions of many experts, Figure 2 shows that the accident cost rate, an indicator of accident severity, increases as pavement width increases, even though the investigated road sections were designed according to the German design guidelines. This result may be because wide pavements are usually assigned high design speed levels. With high design speeds, operating speeds are usually high. Consequently, as operating speeds increase, the severity of an accident, as measured by the accident cost rate, increases too.

Radius of Curve and Degree of Curve

Figure 1(*b*) shows the relationship between accident rate and the radius of the curve as derived from the results of several research studies.

The safe and efficient movement of traffic is greatly influenced by the geometric features of the highway. A review of accident spot maps normally shows that accidents tend to cluster on curves, particularly on very sharp curves. Even though the design engineer possesses detailed information—derived from driving dynamic formulas and standard values—on driving through a curve, accident frequency and severity often do not appear to coincide with the actual driving behavior. Recently, there have been attempts during the design stages to consider the expected operating speeds on curves. This is suggested by a number of researchers—such as Lamm (*32*), Leisch and Leisch (*33*), Koeppel and Bock (*34*), and Hayward et al. (*35*)—and is required in the German design guidelines (*9*) and the Swiss design standard (*11*).

The horizontal alignment of the road may not be characterized by radius of curve only. The same radius of curve in a sequence of similarly tuned radii of curve can have effects on the accident situation other than those in a nontuned sequence of different radii of curve, as is usually the case on most old alignments.

The general opinion today is that the accident risk decreases as the radius of the curve increases or as the degree of the curve decreases. However, different opinions exist regarding the extent of this influence on the accident situation. An investigation by Baldwin (*18*) of U.S. roads with traffic volumes of less than 5,000 vehicles per day indicated that the accident rate decreases as the radius of curve increases. Pfundt (*36*) studied accidents on low- and high-volume roads in the FRG. He indicated that sharp, low-volume roads had high accident frequencies. He also indicated that drivers tended to drive faster on low-volume roads than on high-volume roads. Baldwin (*18*) concluded that the accident rate decreases as curve frequency [radius of less than 600 m (1,970 ft)] increases. On the basis of his investigation, a single curve with a small radius should be regarded as more unfavorable than the same curve within a section with a sequence of curves with similar radii.

An investigation of injury accidents by Coburn (*37*) in the United Kingdom indicated that the accident rate was especially high on curves with radii of less than 175 m (580 ft). For curves with larger radii, he indicated that the increase in traffic safety was relatively small. In a later publication, Coburn (*38*) stated that the accident rate on sharp curves was higher than that on gentle curves.

Balogh (*23*) in Hungary, Raff (*39*) in the United States, Bitzl (*40*) in the FRG, and Vasilev (*41*) and Babkov (*42*) in the former USSR also indicated that the accident rate decreases as the radius of the curve increases.

Knoflacher (*43*) indicated that in the FRG, for radii of up to 800 m (2,625 ft), the percentage of skidding accidents on wet pavements was higher than that on dry pavements; for radii of less than 250 m (820 ft), he found the difference to be statistically significant.

Wilson (*44*) reported that the accident rate on curves with radii of less than 170 m (560 ft) was about five times that on curves with radii of greater than 910 m (2,990 ft). He pointed out the danger that a single curve after a long tangent poses. The dangers that single isolated curves pose was also mentioned by Babkov (*45*) in the former USSR. Because of speed differences before and within the curve, Babkov (*45*) spoke of

- "Safe curves," when the change in speeds was less than 20 percent;
- "Relatively safe curves," when the change in speeds was between 20 and 40 percent;
- "Dangerous curves," when the change in speeds was between 40 and 60 percent; and
- "Very dangerous curves," when the change in speeds was greater than 60 percent.

Pfundt (*36*) indicated that nearly two-thirds of run-off-the-road accidents in the FRG occur in curves or near curved sites. For road sections with different road characteristics, he indicated that the risk of undergoing run-off-the-road accidents increases with the increasing complexity of the alignment. He also indicated that road sections with few curves are more dangerous than sections with many curves.

From the accident data bases of a number of countries, Silyanov (*24*) in the former USSR established a distinct tendency for the accident rate to decrease with an increasing radius of curve. In a study of accidents in Great Britain, O'Flaherty (*46*) also concluded that the accident rate decreases as the radius of curve increases.

Krebs and Kloeckner (*8*) in the FRG determined the following:

1. Accident risk decreases with an increasing radius of curve.
2. Road sections with radii of less than 200 m (660 ft) have accident rates that are twice as high as those on sections with radii of greater than 400 m (1,300 ft).
3. A radius of 400 m provides a cross-point in safety.
4. For radii greater than 400 m, the gain in safety is relatively small.
5. For road sections with radii of between 500 m (1,600 ft) and 800 m (2,600 ft), a slight increase in accident risk is sometimes shown.

Lamm (*32*) explained Item 5 in the following manner:

> Large radii are often associated with low design speeds, such as 80 km/h (50 mph), for which corresponding superelevation rates are between 2 and 3 percent. However, actual 85th percentile speeds on these curves require superelevation rates of at least 5.5 percent. Such a discrepancy between design speed and actual operating speed could influence the accident situation unfavorably. (*32*)

Rumar (*47*) analyzed 14,000 accidents on 9000 km (5,595 mi) of two-lane roads in Sweden. His results showed a reduction in accident rates with increasing radii of horizontal curves.

Statistical analyses by Zegeer et al. (*30*) revealed

1. Significantly higher numbers of accidents on sharper curves, and
2. Accident reductions of up to 80 percent depending on the central angle and the amount of curve flattening.

The research studies reported above have generally shown that there exists a negative relationship between the radius of curve and the accident rate. A considerable increase in accident risk exists in particular on curves with sharp radii, where run-off-the-road accidents most frequently occur, especially after long tangents. In addition to the size of the radius of curve, the road characteristics play an important role. Curves that dictate a significant change in operating speeds and cause inconsistencies in road characteristics are especially dangerous (*1,48,49*). Furthermore, the pavement width influences to a certain extent the magnitude of the accident rate. Curves that are combined with wide pavements do not affect the accident risk as unfavorably as those curves that are combined with narrow pavements.

Research by the authors (*1,5–7,48,49*) demonstrated the following:

1. The most successful parameter in explaining the variability in accident rates was degree of curve.
2. For all lanes combined,
   a. Gentle curvilinear horizontal alignments consisting of tangents or transition curves combined with curves of up to 5 degrees showed the lowest average accident risk;
   b. Accident risk on sections with a change in curve of between 5 and 10 degrees was at least twice as high as that on sections with a change in curve of between 1 and 5 degrees;
   c. Accident risk on sections with a change in curve of between 10 and 15 degrees was about four times that on sections with a change in curve of between 1 and 5 degrees;
   d. For changes in curve of greater than 15 degrees, the average accident rate was even higher.
3. For individual lane widths, the differences in accident rates between lanes of 3.7 m (12 ft) and 3.4 m (11 ft) were more or less more pronounced than those between lanes of 3.4 m (11 ft) and 3.1 m (10 ft).

Typical relationships between degree of curve and accident rates are shown in Figure 3 for the United States and Germany (western) (*49*).

Gradient

The operating speed of a vehicle is influenced by the characteristics of the vertical alignment. Trucks and buses suffer the most on grades, especially on upgrades, where a speed reduction may become significant [Rotach (*50*)]. On downgrades, trucks and buses are often driven at crawl speeds to maintain control for the effect of providing longer braking distances. On longer downgrade sections, with high longitudinal grades, brakes may not adequately slow down a heavy vehicle traveling at high speed and bring it to a stop. For passenger cars, longitudinal grades also lead to a variation in operating speeds, but not in a manner that is as pronounced as that for trucks. It may be concluded that, with increasing longitudinal grades, an increase in the nonhomogeneity of traffic flow could increase the risk of an accident.

A number of studies concerning the relationship between vertical alignment and accident risk have been done.

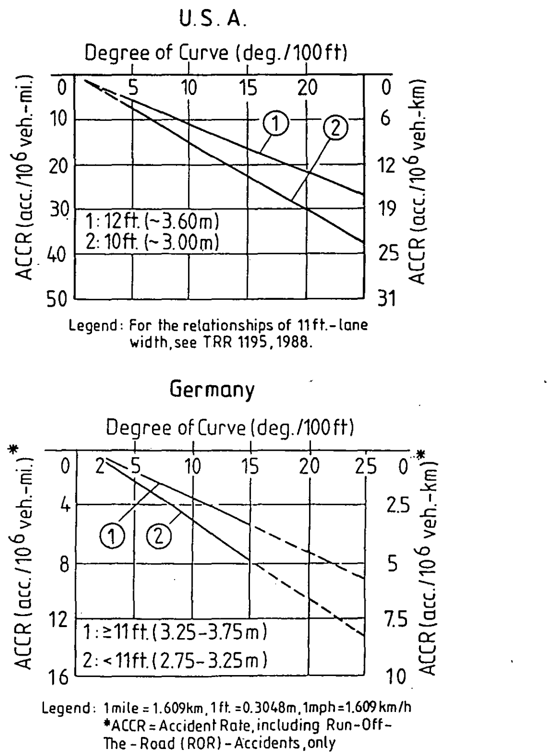


FIGURE 3 Nomogram for evaluating accident rates as related to degree of curve. TRR is *Transportation Research Record*.

An investigation by Bitzl, which is cited by Pucher (*51*), for German two-lane rural roads established a positive relationship between gradient and accident rate. In other words, the accident rate increases as the gradient increases. In another study related to German expressways, Bitzl (*52*) found a marked relationship between grade and accident rate. He indicated that steep grades of 6 to 8 percent produce over four times the number of accidents as gradients of less than 2 percent.

Vasilev (*41*) determined in the former USSR that accident rates were especially high on steep grades. In a study that evaluated data bases from Germany, Great Britain, and the former USSR, Silyanov, (*24*) indicated that the accident rate increased as the gradient increased. Similar results were reported by Babkov (*42*) in the former USSR.

Studies cited by Pignataro (*25*) did show that steeper grades increase the accident rates and skidding accidents on two-lane rural curved sections.

Krebs and Kloeckner (*8*) analyzed accident data for two-lane rural roads in the FRG. They indicated that the accident rate showed a slight increase up to grades of about 6 percent. For grades of more than 6 percent, a sharp increase in the accident rates was noted. Studies by the authors (*5–7*) indicated that grades of up to 5 percent did not have any particular effect on the accident rate.

For two-lane rural highways, the research studies reported above have generally shown that

1. Grades of less than 6 percent have relatively little effect on the accident rate.
2. A sharp increase in accident rate was noted on grades of greater than 6 percent.

Figure 4 illustrates the relationship between the accident rate and accident cost rate and the gradient (*31*) for new designs and redesigns made according to the German design guidelines (*9*). From Figure 4 it can be seen that

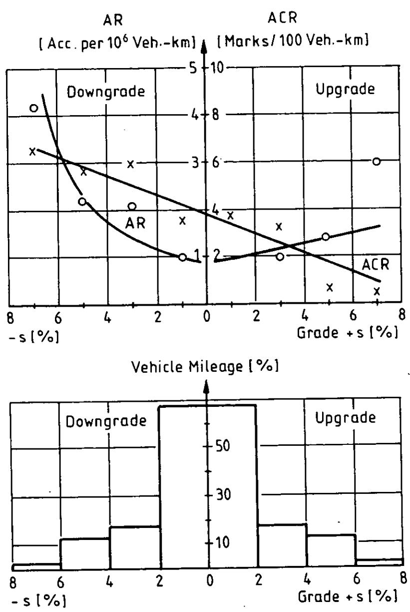


FIGURE 4 Accident rate and accident cost rate versus grade.

1. Longitudinal grades of between 0 and ±2 percent show the most favorable results. With increasing upgrades, the accident rate gradually increases, whereas with increasing downgrades, the risk of being involved in an accident increases exponentially.
2. Between upgrades of +7 percent and downgrades of −7 percent, the accident cost rate gradually increases; this is understandable, since operating speeds are highest on steep downgrades.

Sight Distance

Sight distance, which is dependent on both horizontal and vertical alignments, is of great importance to traffic safety. Hiersche (*53*), in the FRG, pointed out that sight distance is the most important criterion in the design of highway alignments. Krebs and Kloeckner (*8*) did not fully agree with that statement, but said that insufficient sight distances are the cause of many accidents. Meyer et al. (*54*) stated that about one-quarter of all rural accidents originate from overtaking maneuvers for which passing sight distances were not sufficient. Similar results were reported by Netzer (*55*) in the FRG, who determined that passing maneuvers accounted for about 21 percent of all traffic accidents.

An analysis of accidents on U.S. roads by Young (*56*) showed that the accident rate correlated negatively with sight distance. For a sight distance of less than 240 m (790 ft), the accident rate was twice as high as that for a sight distance of more than 750 m (2,450 ft).

In a German investigation, Bitzl and Stenzel (*57*) reported that the frequency of accidents related to improper passing maneuvers sharply increased for sight distances of less than 400 to 600 m (about 1,300 to 2,000 ft).

Sparks (*58*) established a negative relationship between stopping sight distance and accident rate in the United States. Similar results were reported by Silyanov (*24*) in the former USSR and Kunze (*26*) in the FRG.

Another study of accidents on two-lane rural roads in Germany by Krebs and Kloeckner (*8*) determined the following:

1. As sight distance increases, the accident risk decreases.
2. High accident rates were associated with sight distances of less than 100 m (330 ft).
3. With sight distances of between 100 m (330 ft) and 200 m (660 ft), accident rates were about 25 percent lower than those associated with sight distances of less than 100 m (330 ft).
4. For sight distances of more than 200 m (660 ft), no major improvements in accident rates were noted.

Studies by the authors (*5–7*) determined that sight distances of more than 150 m (490 ft) did not have any particular effect on accident rates.

A study of accidents on two-lane rural roads in Texas by Urbanik et al. (*59*) indicated that limited sight distances, especially on crest vertical curves, could cause a marked increase in accident rates. An example would be a sharp horizontal curve hidden by a crest vertical curve.

The research studies reported above have established a negative relationship between available sight distance and accident risk. However, it can be hypothesized that other influencing parameters, such as wide pavements and gentle radii of curve, might also play a part in the observed positive effect of greater sight distances on the accident situation. For narrow road sections, an increase in sight distances could favorably affect traffic safety.

Traffic Volume

When analyzing the relationship between AADT and accident rate, one must keep in mind that road sections with high traffic volumes normally have good designs (i.e., wide pavements, gentle curvilinear alignments, low gradients, etc.). This fact alone plays an important role in the investigation of the relationship between traffic volume and the accident situation.

Goldberg (*60*) investigated accidents on rural two-lane highways in France. For traffic volumes of up to 20,000 vehicles per day, he established a U-shaped distribution between accident rate and traffic volume.

Paisley, in a report by Wilson (*44*, p. 36), studied the effect of traffic volume on accident severity in Great Britain. For fatal accidents, he indicated that accident rate decreased as traffic volume increased. However for accidents with injuries that the accident rate increases as the traffic volume increases. Paisley's study was based on traffic volumes of up to 10,000 vehicles per day.

Roosmark and Fraeki (*61*) analyzed accident types on roads in Sweden with traffic volumes of up to 11,000 vehicles per day. They established the following results:

1. For single-vehicle accidents, the accident rate decreased as the traffic volume increased.
2. For multiple-vehicle accidents, the accident rate increased as the traffic volume increased.

An investigation of accidents on two-lane rural roads in Austria by Knoflacher (*62*) established a U-shaped distribution between accident rate and traffic volume. Accident rate was at a minimum for traffic volumes of between 6,000 and 6,500 vehicles per day. (For traffic volumes of less than 6,000 to 6,500 vehicles per day, single-vehicle accidents dominated. For traffic volumes of more than 6,000 to 6,500 vehicles per day, multiple-vehicle accidents prevailed).

For traffic volumes of up to 10,000 vehicles per day, Lamm and Kloeckner (*63*) in the FRG reported that the accident rate decreased as the traffic volume increased. They indicated that the level of design correlated highly with traffic volume, a result that could explain the favorable trends in accident rates on high-volume roads. Krebs and Kloeckner (*8*) found a negative linear relationship between accident rate and traffic volume of up to 16,000 vehicles per day in the FRG. Research studies by the authors (*5–7*) established a nonsignificant negative relationship between accident rate and traffic volume of up to 5,000 vehicles per day.

In conclusion, although some of the research studies reported above have shown that the accident rate decreases as the traffic volume increases, other investigations established a U-shaped distribution between accident rate and traffic volume. The U-shaped distribution was shown to be valid for multilane highways by Pfundt (*36*), Gwynn (*64*), and Leutzbach et al. (*65*). Leutzbach et al. (*66*) said that the U-shaped distribution between accident rate and traffic volume was also valid for two-lane rural highways.

Design Speed

In addition to the effect of pavement width, radius of curve/degree of curve, gradient, sight distance, and AADT on accident rate, Hiersche et al. (*31*) studied the effect of design speed on accident rate and accident cost rate. Table 1 gives an overview of their results for new alignments designed according to the German design guidelines (*9*). An examination reveals that the accident rate decreases as design speed increases from 60 to 80 km/hr (35 to 50 mph). For design speeds of greater than 80 km/hr (50 mph), the accident rate did not experience an improvement. The accident cost rate, on the other hand, increased as the design speed increased.

These findings are interesting, but further research, including large data bases, is clearly needed on this subject.

SUPERIMPOSITION OF DESIGN PARAMETERS AND DETERMINATION OF BREAKPOINT IN SAFETY

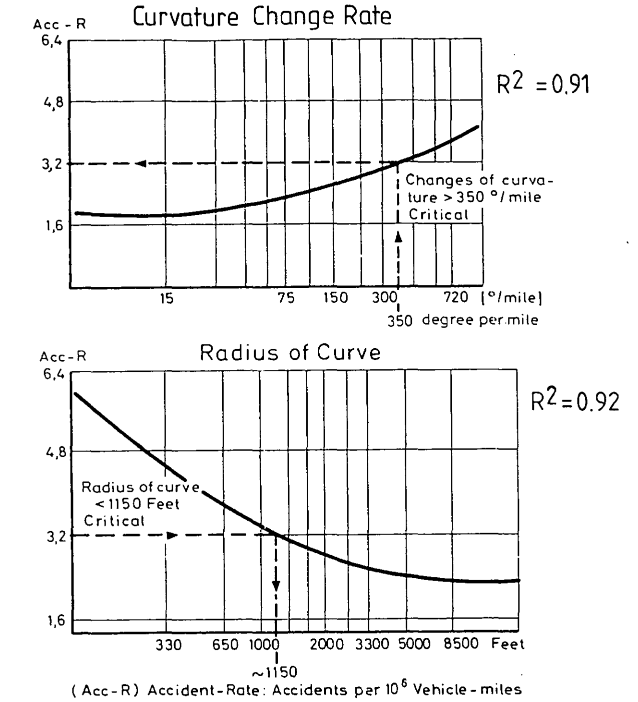
A number of researchers have used regression analysis to obtain quantitative estimates of the effects produced by design and traffic volume parameters on accident rates (*40, 67–74*). However, their findings did not provide any practical applications and did not yield any clue to the level of design parameters, such as degree of curve, above which improvements in traffic safety become particularly important.

Research by the authors (*5–7*), which analyzed the joint effects of several parameters—degree of curve, length of curve, superelevation rate, gradient of up to 5 percent, sight distance, lane width, shoulder width, and AADT—on operating speeds and accident rates, determined that the degree of curve explained most of the variation in the expected operating speeds and accident rates on curved sections of two-lane rural highways. On the basis of previous research (*5–7*), recommendations for good, fair, and poor designs were developed. Readers who are interested in detailed discussions of these recommendations should consult several previously published reports (*49, 75–79*).

Studies conducted at the Institute of Highway and Railroad Engineering at the University of Karlsruhe, Karlsruhe, FRG (*8,17,32*), yielded the results shown in Figures 5 to 8. The data

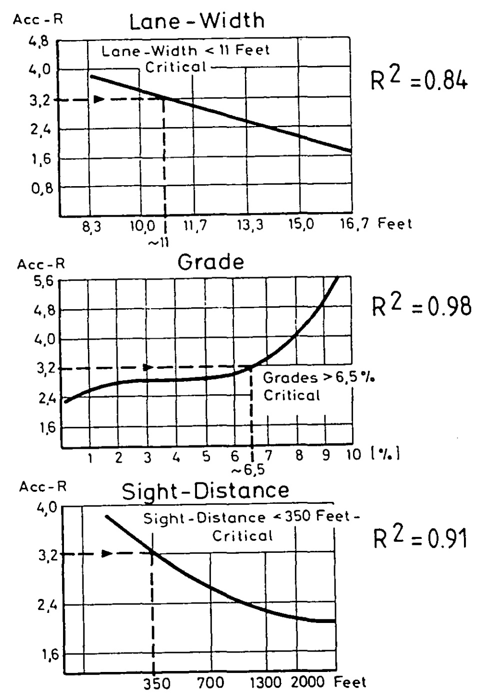
TABLE 1 Effect of Design Speed on Accident Rate and Accident Cost Rate

Design Speed (km/hr)	Vehicle Mileage (Absolute) (10^6 vehicle km)	Vehicle Mileage (%)	Accident Rate (no. of accidents/10^6 vehicle km)	Accident Cost Rate (DM/10^2 vehicle km)
60	52.3	14.6	2.12	3.62
70	18.0	5.2	1.78	3.85
80	234.5	65.7	1.15	4.21
100	52.0	14.5	1.11	5.21



Legend: 1 mile = 1.609km, 1 ft. = 0.3048m, 1mph = 1.609 km/h

FIGURE 5 Accident rate as function of curvature change rate and radius of curve on two-lane rural roads.



Legend: 1 mile = 1.609km, 1 ft. = 0.3048m, 1mph = 1.609 km/h .

FIGURE 6 Accident rate as a function of lane width, grade, and sight distance on two-lane roads.

base covered 4 years of accident experience (14,200 accidents) on 1162 km (722 mi) of two-lane roadways in western FRG. Figures 5 and 6 show that there is a definite correlation between accident rate and curvature change rate, radius of curve, lane width, gradient, and sight distance. However, the results in Figures 5 and 6 do not yield a clue to the level of design parameters above which improvements in traffic safety become particularly important. In other words, the results do not present a minimum level of safety or a maximum level of unsafety (*17*). [Curvature change rate is the absolute sum of the angular changes per section length of roadway with similar road characteristics. It has been used in the German design guidelines since 1973 (*9*).] For single curves, the curvature change rate formula reduces to just the degree of curve formula (*77–79*) (Table 2).

A number of studies conducted in Europe and the United States (*32,34,49,77,80*) have shown that curvature change rate correlates highly with operating speeds and accident rates. As shown in Figure 7, an increase in curvature change rate leads to a decrease in operating speeds. Furthermore, for new designs—designed according to the German design guidelines (*9*)—Lamm (*17*) indicated that curvature change rates greater than or equal to 250 gon/km (350 degrees/mi) produced relatively high accident rates. It should be noted that for new designs and redesigns in Germany, curvature change rates of greater than 250 gon/km (350 degrees/mi) are used in very few cases (Figure 7).

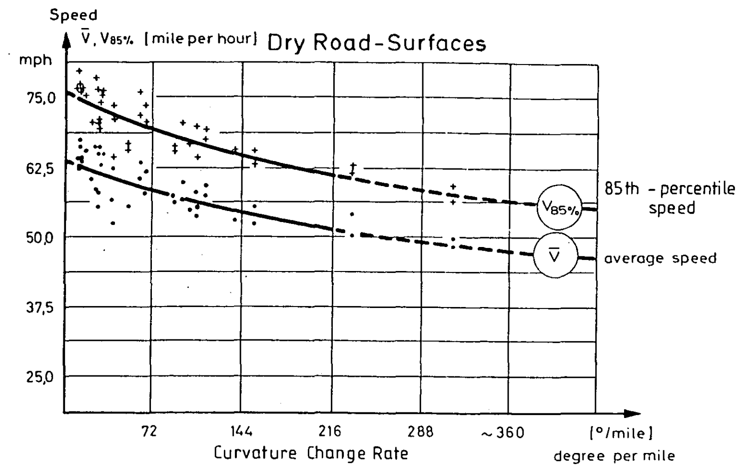
Lamm (*17*) concluded, "If curvature change rate of 350 degrees per mile is the highest acceptable level of curvature in modern geometric design guidelines, then the accident rate corresponding to this curvature change rate should be regarded as the break-point between levels of safety and un-safety." On the basis of the data in Figure 5 and Table 2 an accident rate of 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi) corresponds to a curvature change rate of 250 gon/km (350 degrees/mi) and a radius of curve of 350 m (1,150 ft) or a degree of curve of about 5 degrees. Furthermore, Lamm suggested that design parameters, such as radius of curve, lane width, and gradient, should be laid out during the design stages (for new designs or redesigns) in such a way that when the road is in full operation the accident rate should not be allowed to exceed 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi); this corresponds to a level of safety/unsafety of $1 - (2 \times 10^{-6}) = 0.999998$, or a 99.9998 percent chance that an accident will not occur.

Despite this high percentage, Lamm indicated that decisive endangerments could still be expected. To illustrate this point, he gave the following example:

> For a safety level of 100% . . . ADT of 10,000 vehicles per day . . ., it can be estimated that 3,650,000 (365 × 10,000) vehicles per year would pass a section-kilometer without being involved in accidents. However, according to the proposed level of safety/un-safety (99.9998%), only 3,649,993 vehicles would pass safely; that means, 7 vehicles would be involved in collisions on the observed section-kilometer. (*17*)

From Figures 5 and 6, an accident rate of 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi) corresponds to

- Radius of curve of about 350 m (1,150 ft),
- Lane width of about 3.3 m (11 ft),
- Grade of about 6.5 percent, and
- Sight distance of about 100 m (350 ft).



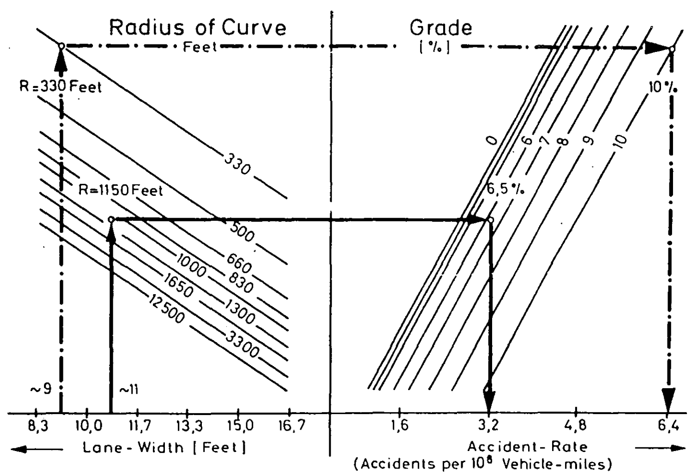
Legend: 1 mile = 1.609 km, 1 ft. = 0.3048 m, 1 mph = 1.609 km/h

FIGURE 7 Relationship between operating speed and curvature change rate on two-lane rural roads.

Falling short of or exceeding the above values could result in an accident rate of greater than 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi). It should be noted that AASHTO's design guidelines appear to meet the minimum requirements when they recommend lane widths of 3.3 m (11 ft) and 3.6 m (12 ft), maximum grades of 6 to 7 percent—for design speeds of between 80 km/hr (50 mph) and 95 km/hr (60 mph) in mountainous topography, and a stopping sight distance of about 100 m (350 ft) for a design speed of 80 km/hr (50 mph). The German design guidelines show similar results.

For future designs, the use of radii of curve of less than 350 m (1,150 ft) should be carefully considered. For safety reasons, curvature change rates of greater than [350 degrees/mi (5 degrees of curve)], pavement widths of less than 3.3 m (11 ft), gradients of more than 6.5 percent, and sight distances of less than 100 m (350 ft) should be avoided. For responsible agencies, policy makers, and so on, the question here becomes, Which is more important —safety, economics, or the environment? This decision must be made on a case-by-case basis.

Up to now, the risk of an accident, as measured by the accident rate, was regarded as a function of single design parameters. Since the accident situation cannot be described by just one design parameter, as noted previously, Krebs and Kloeckner (*8*) studied the joint impacts of several design parameters, including radius of curve, lane width, gradient, sight distance, and traffic volume on accident rate. Sight distance was later removed from the analyses



Legend: 1 mile = 1.609 km, 1 ft. = 0.3048 m, 1 mph = 1.609 km/h

FIGURE 8 Nomogram for determining accident rate as a function of lane width, radius of curve, and grade on two-lane roads.

TABLE 2 Relationship Between U.S. Design Parameter Degree of Curve and German Design Parameter Curvature Change Rate for Curves Without Transition Curves

"Degree of curve" DC	"Curvature Change Rate" CCR
• Definition $DC_{ft} = \frac{360^\circ}{2\,\pi\,R}\left[\frac{Degree}{100\ ft}\right]$ $= \frac{5729,6}{R}\left[\frac{Degree}{100\ ft}\right]$ DC_{ft} : radius of curve [ft]	• Definition (gon related to 400°) $CCR = \frac{\sum_{i=1}^{n} \lvert\gamma_i\rvert}{L}\left[\frac{gon}{km}\right]$ γ_i = change of angle (angular change) L = length of road section [km]
• in gon / 100 m $DC_m = \frac{6370}{R}\left[\frac{gon}{100\ m}\right]$ R = radius of curve [m]	• for one circular curve without transition curves $CCR = \frac{\frac{L_{cr}}{R} \times 63,7}{L}\left[\frac{gon}{km}\right]$ L_{cr} = length of circular curve [m] R = radius of curve [m]
• with gon / km $DC_m = \frac{63700}{R}\left[\frac{gon}{km}\right]$ R = radius of curve [m]	• with $L = L_{cr}/1000$ [km] $CCR = \frac{63700}{R}\left[\frac{gon}{Km}\right]$ R = radius of curve [m]

Relationship : $DC_{ft}\left[\frac{Degree}{100\ ft}\right] \times 36,5 \approx CCR\left[\frac{gon}{km}\right]$

36,5 [-] = conversion factor between DC_{ft} (Imperial System) into CCR (Metric System)

because it correlated highly with radius of curve. The same was true for curvature change rate. Traffic volume was also excluded because it did not affect the accident rate significantly. As a result of the study, Figure 8 was developed. Examination of Figure 8 leads to the following interesting results:

- Use of the design parameters recommended above results in an accident rate of 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi).
- Use of minimum design standards, such as German design guidelines, results in an accident rate twice as high as that recommended.

Once again, the proposed breakpoint in safety, as related to the accident rate, was obtained even when several design parameters were superimposed.

It should be noted that one unfavorable design parameter should not be superimposed on others. By correctly applying Figure 8, a high accident rate resulting from one unfavorable design parameter could be taken care of, at least partially, by proper selection of the other design parameters.

CONCLUSION

As a result of the present review, the following important conclusions can be drawn.

Influence of Pavement Width

- A distinct tendency for accident rates to decrease with increasing pavement width up to about 7.5 m (25 ft) was established.

Influence of Radius of Curve/Degree of Curve

- A negative relationship between radius of curve and accident rate was established.
- The same radius of curve in a sequence of similarly tuned radii can have effects on the accident situation other than those in a nontuned sequence of different radii, as is usually the case on most old alignments.
- For radii of less than 200 m (660 ft), the accident rate is at least twice as high as that on a radius of 400 m (1,300 ft). For radii of greater than about 400 to 500 m (1,650 ft), an increase in radius leads to a low-level safety gain.
- The most successful parameter in explaining the variability in accident rates was the degree of curve or curvature change rate. [On the basis of this parameter, recommendations for good, fair, and poor designs that were based on operating speeds and accident rates were made for the United States and Germany (*5–7,49,75–78*).]

Influence of Gradient

- Gradients of less than 6 percent have a low impact on the accident situation. For gradients of more than 6 percent, a sharp increase in the accident rate was noted.

Influence of Sight Distance

- A significant, positive relationship between sight distance and radius of curve was established.

Influence of AADT

- A negative relationship between traffic volume and road traffic accidents was established. Run-off-the-road accidents were found to decrease with increasing AADT up to 10,000 vehicles per day. Newer investigations report a U-shaped distribution between accident rate and traffic volume.

Superimposition of Design Parameters/BreakPoint in Safety

- Strong correlations between a number of design parameters and accident rates were established.
- A breakpoint in safety, or an accident rate of 2.0 accidents per 10^6 vehicle km (3.2 accidents per 10^6 vehicle mi), was proposed. Also proposed were limiting values for design parameters corresponding to this breakpoint in safety. Falling short of or exceeding those limiting values could mean that the breakpoint in safety is exceeded. This breakpoint in safety should be considered the borderline between levels of safety and unsafety.

It is not the intention of the authors to give the impression that the limiting values proposed in this paper are generally valid, since the study was mainly related to the influence of the road itself on traffic safety. As noted earlier, there are many factors that may exhibit a measurable influence on driving behavior and traffic safety on two-lane rural highways. These include, but are not limited to, human factors, physical features of sites, the presence and the action of traffic, legal issues, environmental factors, and vehicle deficiencies. All of these therefore constitute a complex mix of various causes of traffic accidents, of which the road itself represents only one factor, but a very important one.

Because accident cost rate, an indicator of accident severity, was shown in the present study to increase with increasing design speed and pavement width and decreasing grade, the authors propose that further studies with large data bases be conducted in this field.

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