Coordination of Horizontal and Vertical Alinement with Regard to Highway Esthetics

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The vertical and horizontal designs of highways should have a pleasing appearance when combined together. They should also fit gracefully into their surroundings and become acceptable components of the landscape as viewed from outside the highway. The coordination or proper fitting together of the horizontal and the vertical alinements is an important technique for achieving an esthetically pleasing highway alinement design. Even though the safety benefits of esthetically pleasing highways have not been well documented in the past, the literature contains statements about the subtle interrelationship between highway esthetics and highway safety; that is, those things that make a highway beautiful also can make it safer for traffic. In addition, an esthetically pleasing highway also appears to be safer to the users, which is important for their enjoyment of that highway. Definitive guidelines for safe and esthetically pleasing three-dimensional alinements are presented. The recommended practices of both Germany and the United States are discussed and compared. A safety evaluation process called *curvilinear alinement* and its application to superimposed vertical and horizontal alinements are discussed. Several specific items related to highway esthetics and related safety issues are recommended for consideration for inclusion in the next AASHTO policy on geometric design of highways and streets (Green Book).

The essential form of highways expresses their function, which is to move people and goods safely and rapidly from one place to another. Highways should have a pleasing appearance. They should fit gracefully into their surroundings and become acceptable components of the landscape as viewed from outside the highway (*1*). The coordination or proper fitting together of the horizontal and vertical alinements is an important technique for achieving an esthetically pleasing highway design.

In the United States highway esthetics is generally considered a desirable goal in design because anything worth doing is worth doing well. The safety benefits of esthetically pleasing highways have not been well quantified; nonetheless, in *Practical Highway Esthetics* (*1*), it is stated that there is a subtle interrelationship between highway esthetics and highway safety. Measures, such as smooth continuous alinement, wide recovery areas, broad rounded ditches, flat slopes, and erosion control, all of which make a highway beautiful, also make it safer for traffic. Not only is the highway actually safer but it also appears to be safer to the driver and passengers, which is important to their enjoyment of the roadsides and the scenery. *Practical Highway Esthetics* (*1*) also makes the case for "safety in variety"; that is, monotony is the enemy both of good esthetics and safe operation, and it dulls the enjoyment of the visual experience and diminishes the alertness that is essential for safe driving.

The 1990 Green Book (*2*) promotes the concept of alinement coordination principally for its esthetic value. In addition, it mentions that excellence in design owing to the coordination of vertical and horizontal alinements increases usefulness and safety, encourages uniform speed, and improves road appearance, and it does these things almost always without additional cost.

The formal study of the esthetics of high-speed-road alinement began in Germany in the 1930s with the work of Fritz Heller, Hans Lorenz (*3*), and others. The German engineers went to considerable trouble and expense to eliminate or modify combinations of vertical and horizontal curvatures that looked awkward when viewed in perspective from a low angle. The following definitive guidelines for achieving a safe and esthetically pleasing three-dimensional alinement are taken from German studies made in recent years.

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THREE-DIMENSIONAL ALINEMENT

This section is based on German *Guidelines for the Design of Rural Roads, Part II: Alinement, Section 2: Three Dimensional Alinement* (*RAL-L-2*) (*4*) and the newest knowledge in this field (*5,6*).

By applying perspective methods, the view of the road can be shown in a single drawing. In these guidelines, only the perspective view of the driver is considered. Other perspective views should not be used for the three-dimensional evaluation of the road. For example, a perspective view from a bird's eye may show a sharp curve [Figure 1(*a*)], which in reality is not critical because of driving dynamics or optical deficiencies [Figure 1(*b*) and (*c*)].

The goal of these guidelines is to produce the best alinement that provides optimum safety and traffic quality. Well-balanced, curvilinear road sections in which each single design element contributes to a good road characteristic should be created. Well-balanced sections eliminate unsafe feelings and driver discomfort. With the use of these guidelines, the designer will be able to recognize and evaluate preliminary road designs that result from superimposing selected horizontal and vertical design elements. In this way the designer can create three-dimensional design elements that achieve perceivable and safe road characteristics.

Elements of Three-Dimensional Alinement

Although the design of a road or roadway plans may consist of individual elements, the combination of horizontal alinement

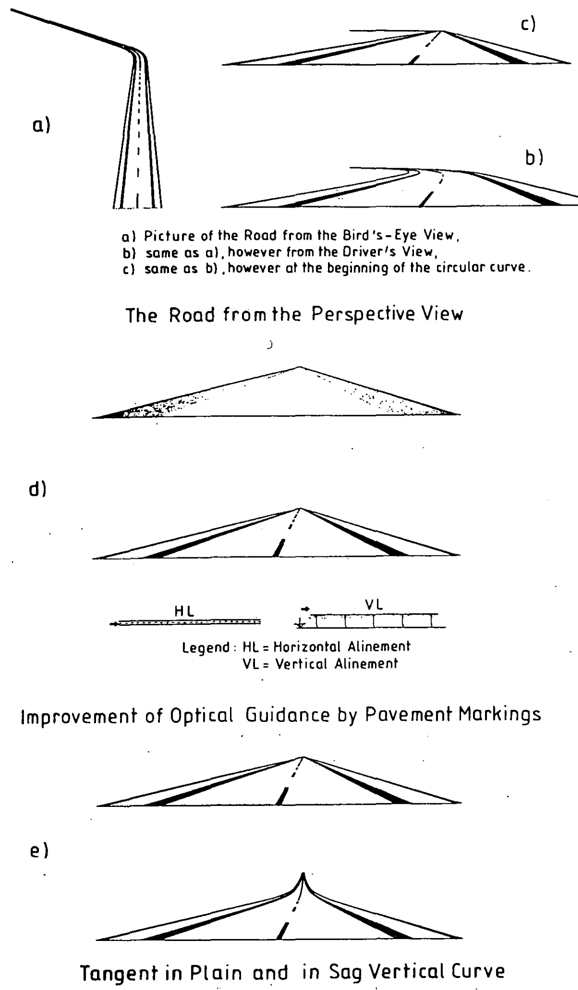

FIGURE 1 Examples of different perspective views (*4*). The road from different perspective views: (*a*) picture of the road from the bird's eye view; (*b*) same as (*a*), however from driver's view; (*c*) same as (*b*), however at the beginning of the circular curve; (*d*) improvement in optical guidance by pavement markings; and (*e*) tangent in plain and in sag vertical curve.

(plan) and the vertical alinement (profile) results in a spatial or three-dimensional creation because of the superimposition of all design elements. The resulting driving space can be described in its sequence with the concept of *road characteristics*. It includes the whole of the structural elements and determines the driving behavior of the motorist. Road characteristics should not be changed greatly over short roadway sections. A consistent sequence of images of the driving space should be balanced in relationship to the design parameters among themselves (relation design). Different roadway sections should be connected by gradual transitions with each other (*5*) (see the paper by Lamm and Smith, this Record).

Thus, in the design of highway alinements, horizontal and vertical design elements are necessarily superimposed. Combining the cross-section of the road, which includes shoulders, pavement width, pavement lane, and edge markings, with horizontal and vertical design elements results in a three-dimensional design element. The design of any road is made up of a series or a sequence of three-dimensional design elements. Typical three-dimensional design elements become important for every new highway geometric design guideline (Figure 2).

Design of Driving Space

The creation of a good view of the road (optical guidance by the roadway) requires a tuned design of the roadway edge (surface guidance) and of the driving space (spatial guidance) with regard to the function of the road. It can be influenced positively by the sensible selection and use of all given possibilities (three-dimensional design elements of the roadway, pavement markings, slopes, embankments, plantings, engineering structures, traffic signing, and directional signing) (*5*).

A good view of the road (optical guidance) is an important issue in conjunction with safety and traffic flow along a roadway section. Usually this can be achieved if the view of the road appears to blend into the surroundings and if the direction of the road is readily apparent.

Furthermore, the optical guidance by the road is created by the perspective view of the road. For example, the direction of the road becomes more obvious as pavement edges and lane lines are marked more distinctly [Figure 1(*d*)]. Pavement markings are of special significance in superelevated sections and where lanes are widened (surface guidance). Detailed information, including numerous examples that show the three-dimensional alinements of highways (spatial guidance), is given in Figures 3 and 4.

Horizontal Design Elements

Tangent

Long tangent sections of highways are monotonous and fatiguing. They can mislead the driver into traveling at excessive speeds and increase the danger from headlight glare at night. Therefore, long tangents with constant grades must be avoided, and the maximum length in the German design guidelines is limited numerically, in meters, to 20 times the design speed in kilometers per hour.

The unfavorable impression caused by long tangents can be reduced by the use of a sag vertical curve with a long length and large radius [Figure 1(*e*)].

Short tangent segments between two horizontal curves in the same direction should be avoided [Figure 3(*a*)]. If such designs cannot be eliminated, it is important that a minimum length be used between the two curves. The minimum length of the tangent segment should correspond to a numerical value, in meters, about four to six times the design speed in kilometers per hour.

Curves

Short circular curves between tangents appear as optical breaks [Figure 3(*b*)] if they are viewed from a long distance. Such an optical break can be avoided [Figure 3(*c*)] by connecting the two tangents with a long horizontal curve (see paper by Lamm and Smith, this Record).

Vertical Design Elements

Tangent Segments

A short tangent used between two succeeding sag vertical curves can give the impression of a crest vertical curve [Figure 3(*d*)] and

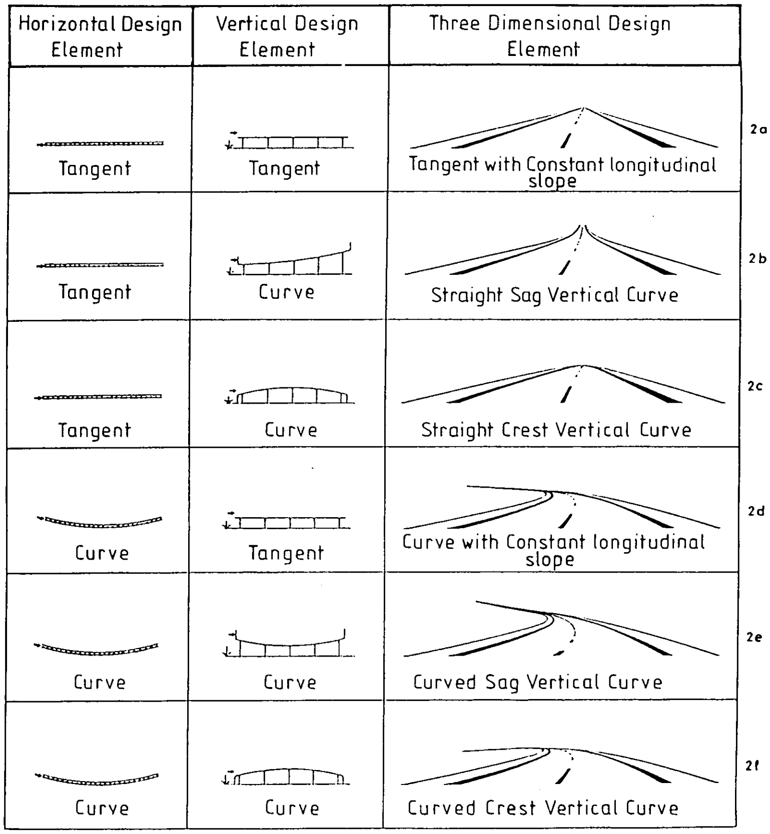

FIGURE 2 Three-dimensional design elements originated by superimposing tangents and circular curves (*4*).

should be avoided. A better solution, a long sag vertical curve, is shown in Figure 3(*e*). The same is true for a short tangent between two succeeding crest vertical curves. Such a design may give the impression of a sag vertical curve [Figure 3(*f*)] and should be avoided. A better solution, a long crest vertical curve, is shown in Figure 3(*g*). In addition, the greater the distance a motorist can see ahead on the road, the longer a sag vertical curve should be to eliminate visual breaks.

Sag Vertical Curves

The sag vertical curve is the three-dimensional design element with the best visual qualities and optical guidance [Figure 1(*e*)]. However, there is one exception: the use of a short sag vertical curve between long sections with constant grades should be avoided. In this case it does not matter whether the horizontal alinement is on a tangent section or a curve [Figures 4(*a*) and 4(*b*), respectively]. In both cases, a visual break in the perspective view occurs. The length of sag vertical curves on embankments usually can be increased considerably without a large increase in earthwork costs.

Crest Vertical Curves

The crest vertical curve represents the most critical design element when considering good visual qualities. The influence of a crest vertical curve is especially critical with short lengths that cause insufficient sight distances. Crest vertical curves with minimum stopping sight distances should be avoided on the mainline roadway if at all possible. The main consideration in using longer lengths is earthwork costs. With the availability of user-friendly earthwork programs and the perspective plot capabilities of the programs, it is now an easy task to design and test many alternative profiles.

Consequences

On mainline roadway sections, avoid visual breaks that are the result of short horizontal and vertical curves or their combination. Instead, strive to use generous design elements. Short curves lead to inconsistencies at the roadway's edge. Compare Figures 3(*a*) and 3(*b*) with Figure 3(*c*) and Figures 3(*d*) and 3(*f*) with Figures 3(*e*) and 3(*g*). Figures 4(*a*) and (*c*) also show designs that should be avoided.

Furthermore, the following should be avoided:

- Diving: the partial disappearance of the road from the driver's view with reappearance in the extension of the just-passed roadway section [Figure 4(*d*)].
- Jumping: similar to diving but with displaced reappearance [Figure 4(*e*)].
- Fluttering: multiple diving or a rapidly rolling profile [Figure 4(*f*)].

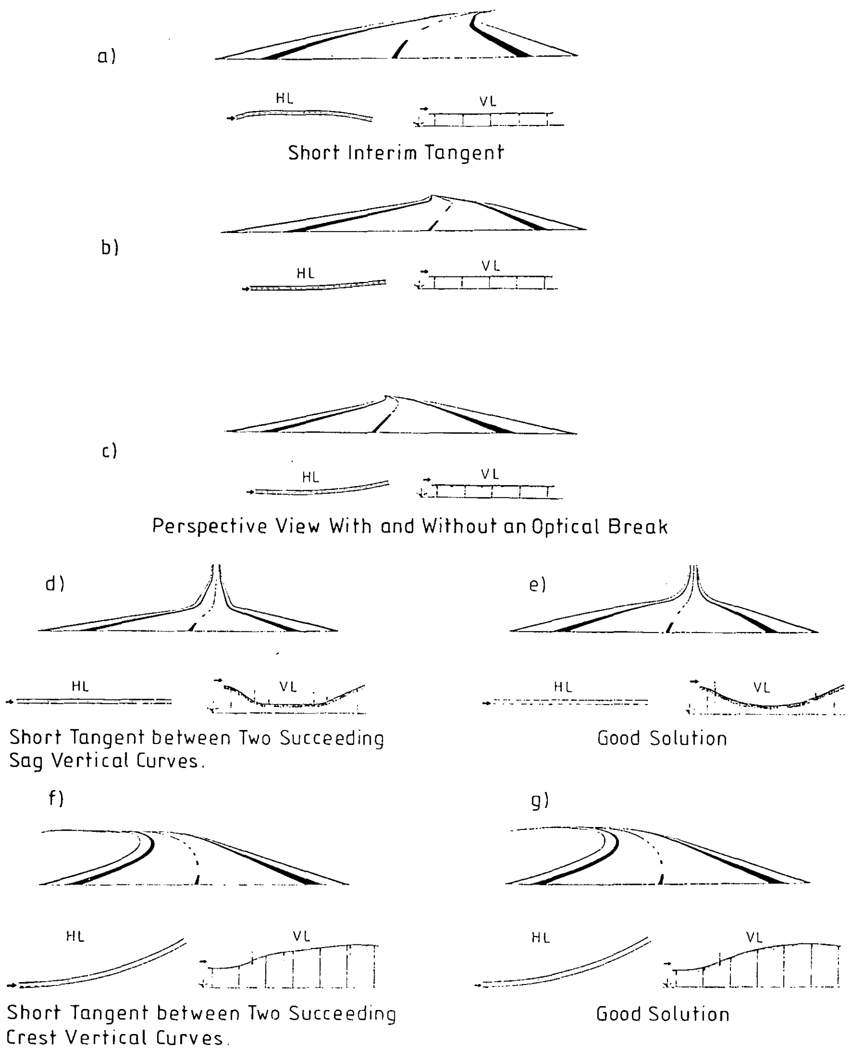

FIGURE 3 Examples of poor and good solutions in Germany (*4*): (*a*) short interim tangent; (*b*) and (*c*) perspective view with and without an optical break; (*d*) short tangent between two succeeding sag vertical curves and (*e*) good solution; (*f*) short tangent between two succeeding crest vertical curves and (*g*) good solution.

- Broken-back vertical curve: a short tangent section between two sag vertical curves [Figure 3(*d*)].

All these designs may lead to critical driving maneuvers especially because of visual misconceptions.

SEQUENCE OF DESIGN ELEMENTS AND SUPERIMPOSITION OF ELEMENTS

Horizontal Alinement

The safety of a motorist is not potentially impaired by the use of a series of smaller-radius curves for a winding alinement. Despite the sharp curvature, a more or less curvilinear alinement does exist [Figure 5(*a*)]. However isolated sharp curves in the course of a gentle alinement are noncurvilinear, can be considered dangerous, and should be avoided [Figure 5(*b*)]. Reliable margins for the range of radii of curve sequences that ensure satisfactory operational practices are given by the authors in another paper, this Record. The same concept can be applied to sight distance problems along the course of a road.

Vertical Alinement

Note that in U.S. practice vertical curves are portions of vertical parabolas and the length (L) of the vertical curve is usually specified in the design.

In German practice the radius (R) of a circular arc is usually selected or specified for vertical curve design. Note, however, that the Germans replace the circular vertical curve with a vertical parabola for ease in computing elevations along the vertical curve.

It can be shown that a circular arc can be used to replace a parabola (and vice versa) as the typical highway vertical curve with almost no error. In the United States the rate of vertical

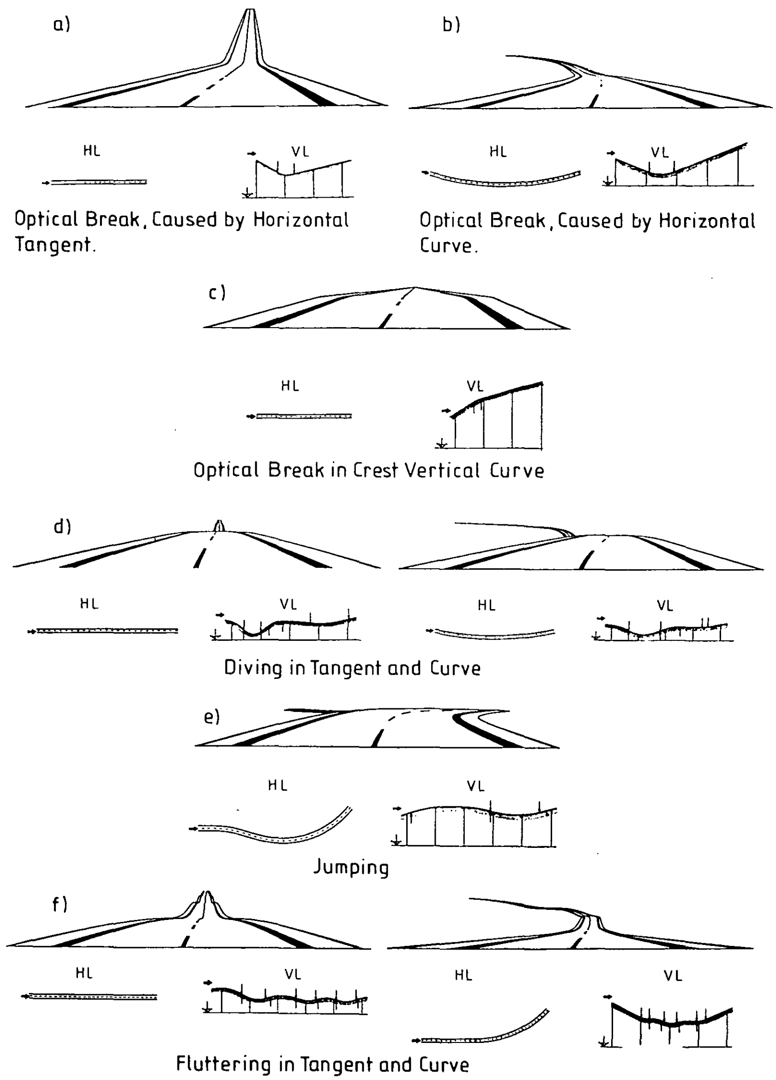

FIGURE 4 Design cases to be avoided (*4*): (*a*) optical break caused by horizontal tangent; (*b*) optical break caused by horizontal curve; (*c*) optical break in crest vertical curve; (*d*) diving in tangent and curve; (*e*) jumping; (*f*) fluttering in tangent and curve.

curvature (K) is the length (in feet) of vertical curve (a portion of a vertical parabola) per percent change of grade (A). The length of vertical curve is, therefore, written $L = KA$ (*2*).

It can be shown that the radius of an equivalent vertical parabolic curve is very close to $R = 100K$ (feet) or $R = 30\ K$ (meters) for typical highway designs.

To provide stopping sight distance (U.S. criteria) for a design speed of 110 km/hr (70 mph), the minimum recommended K values range from 220 for sags to 540 for crests (*2*). The minimum recommended radii would then range from 6700 m (22,000 ft) for sags to 16 200 m (54,000 ft) for crests.

For sequences of design elements in the vertical plane, the following must be considered (Figure 5).

1. In hilly topography, the radii of crest vertical curves should be larger than the radii of sag vertical curves. This concept provides a longer sight distance for the crest vertical curve [Figure 5(*c*)]. Significantly longer sight distances provide a greater feeling of safety to the driver.

2. For smaller differences in the elevation of a roadway (up to 10 m) and on a roadway with a flat topography, the radii of sag vertical curves should be larger than those of crest vertical curves. This concept takes into consideration that a motorist can see the road for a longer distance in flat terrain and therefore provides the motorist with a smoother, more visually satisfying view of the course of the road [Figure 5(*d*)].

3. Quick sequences of short crest and sag vertical curves should be avoided.

Superimposition of Elements

With respect to the superimposition of horizontal and vertical alinements, the ratio between radii of horizontal curves (R) and radii of sag vertical curves (H_w) cannot be selected arbitrarily but

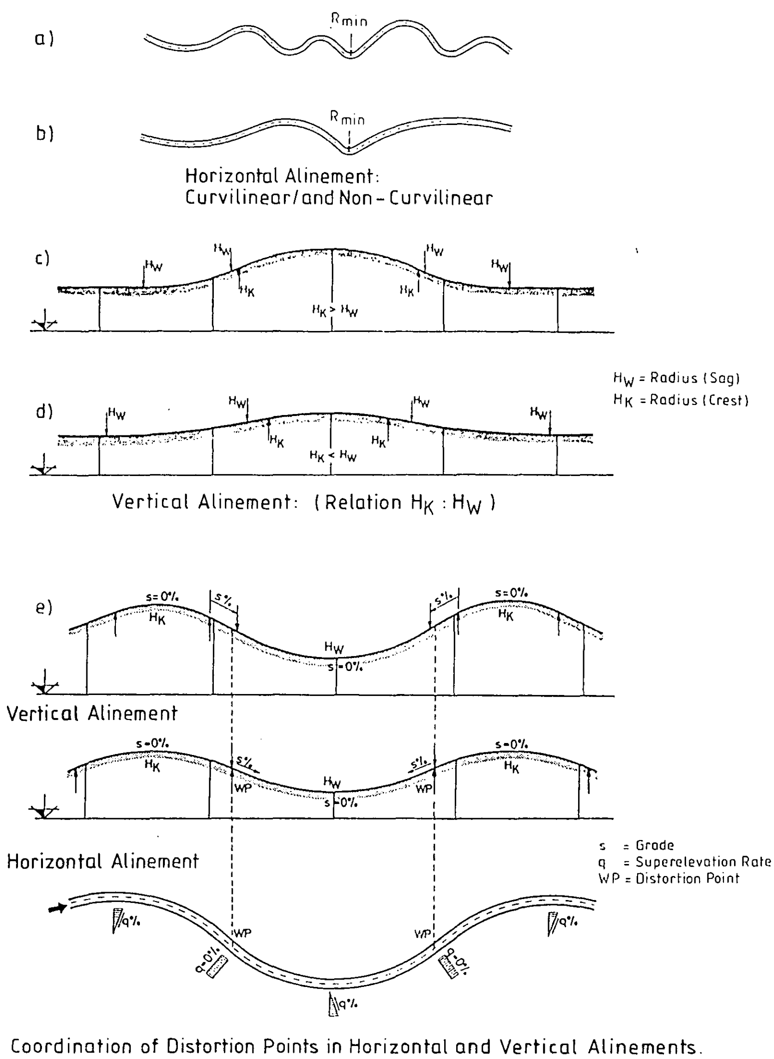

FIGURE 5 Element sequences and superimposition (Germany): (*a*) and (*b*) horizontal alinement: curvilinear and noncurvilinear; (*c*) and (*d*) vertical alinement (relation H_K:H_W); (*e*) vertical alinement, horizontal alinement, and coordination of distortion points in horizontal and vertical alinements.

must be related or tuned to each other. To achieve a satisfactory three-dimensional solution, experience shows that the ratio R/H_w should be as small as possible. The ratio should be in the range of 1/5 to 1/10.

If these values are exceeded, a perspective analysis of the roadway section is recommended. This can be accomplished easily by using modern computer systems and user-friendly earthwork programs now available. Such programs are usually part of a computer-aided drawing and design (CADD) system and also involve the use of perspective plot programs.

In flat topography, the radii of crest and sag vertical curves should be longer than the radii of horizontal curves. Furthermore, a favorable view of the road is normally guaranteed if the distortion (revolving) points of both the horizontal and vertical alinements are set to approximately coincide. This is shown in Figure 5(*e*). This can be accomplished if the curves in both the horizontal and vertical alinements are placed at approximately the same location and have about the same length. In this way, the distortion points then lie at about the same spot and a sufficient longitudinal slope for drainage is guaranteed at the zero points of the superelevation rate.

Therefore, with such coordination the number of distortion points in the horizontal and vertical planes should always be the same. In addition, by designing areas with low superelevation rates in this way, sufficient longitudinal grades for drainage are attained, and in areas with low longitudinal grades sufficient superelevation is available.

In hilly or mountainous topography with steeper longitudinal grades, it may be desirable to select a segment of constant grade between the ends of consecutive crest and sag vertical curves [see upper vertical alinement of Figure 5(*e*)]. In this case, the distortion point of the horizontal alinement should be set nearer the beginning of a sag vertical curve. This type of design then enables the driver to recognize, in advance, the distortion point of the horizontal alinement.

If the local topography does not allow the designer to fit together the distortion points as shown in Figure 5, it then becomes desirable for safety reasons to allow drivers to perceive the exact course of the roadway as soon as possible. Because the largest part of the road is perceived visually, it is necessary to design the visual image on the basis of the driver's perspective. This can best be accomplished by designing horizontal curves to lead crest vertical curves. Designing a highway in this way allows motorists to perceive where the highway is going before they get to the curve (*5*). For example, the views of the road shown in Figure 4(*d*) and 4(*e*) should be avoided.

U.S. RECOMMENDED PRACTICE

In this section some currently recommended practices in the United States are presented and are related to the practices recommended in Germany described above. In some cases the U.S. literature may not properly credit the German sources.

The following are some guiding rules for the satisfactory three-dimensional appearance of highway alinement. They are taken from *Practical Highway Esthetics* (*1*), The 1990 Green Book (*2*), Pushkarev (*7*), and Cron (*8*).

• Curvature in the horizontal plane should be accompanied by comparable curvature in the vertical plane, and vice versa (*1,7*). Thus, the grade line for a long flat horizontal curve should be smooth and flowing and not interrupted by short dips and humps. Figure 6(*a*) shows an unpleasant view, and Figure 6(*b*) shows a more pleasing view.

Comment: The earlier discussion of vertical design elements (sags) [Figures 4(*a*) and (*b*)] and consequences [Figure 4(*f*)] show what can happen if this recommended practice is not followed.

• Awkward combinations of curves and tangents in both the horizontal and vertical planes should be avoided (*2*, item 4, p. 294). The most prominent of these combinations is the broken-back gradeline, that is, two sag curves in the same direction connected by a short tangent [Figure 6(*c*)]. Vertical broken backs are visibly prominent only when short vertical curves are used. The broken-back appearance can be corrected by using longer vertical curves at each end of the short grade tangent or by eliminating the short grade tangent. The remedy for horizontal broken-back curves is to replace the tangent with a flat curve or to use at least 500 m (1,500 ft) of tangent section between the two horizontal curves in the same direction.

Comment: The earlier discussion of vertical design elements (tangents) and consequences [compare Figure 3(*d*) and 3(*e*)] address this issue and agree.

• Horizontal and vertical curvatures should be coordinated to avoid combinations that appear awkward when viewed from a low angle (*1,2,7,8*). Ideally, the vertices of horizontal and vertical curves should coincide [Figure 6(*d*)]. This statement corresponds to the earlier discussion of the superimposition of elements [Figure 5(*e*)]; however, this is not always possible. A reasonably satisfactory appearance will result, however, if the vertices of the horizontal and vertical curves are kept apart by not more than one-quarter phase. Skipping a phase in the plan while keeping the profile vertices in phase will result in reasonably good coordination and appearance [Figure 6(*e*)]. A shift of one-half phase will result in poor coordination and appearance, as shown in Figure 6(*f*).

Changes in horizontal and vertical curvature should not occur at or near the same point. When combining horizontal and vertical curves, the former should be somewhat longer than the latter, and where the vertices of the curves are slightly out of phase, the vertical curve should lie completely within the horizontal curve.

According to Rose (*1*, p. 59,60) the coordination of horizontal and vertical alinements is seldom a serious problem when the radius of a horizontal curve is 1800 m (6,000 ft) or longer and when vertical curves are longer than about 128 m (420 ft) for each percentage of gradient change. Alinements with sharper curvatures than this should be studied for their three-dimensional appearances with computer-drawn perspective plots.

Comments: note that the 128 m (420 ft) per percent grade change is the K value, that is, the rate of vertical curvature [length (in feet) per percent of grade change (A)]. As noted earlier, this would translate into a minimum vertical curve radius of 42,000 ft ($R = 100K$) or 12 600 m ($R = 30K$, in meters).

The ratio of the horizontal curve radius to the vertical curve radius is 1800/12 800 m (6,000/42,000 ft), or 1/7, and is within the 1/5 to 1/10 minimum ratio recommended in Section 3.2.

• In the Green Book (*2*, item 3, p. 296) the following is noted:

> Sharp horizontal curvature should not be introduced at or near the top of a pronounced crest vertical curve. This condition is undesirable in that the driver cannot perceive the horizontal change in alinement, especially at night when the headlight beams go straight ahead into space. The difficulty of this arrangement is avoided if the horizontal curvature leads the vertical curvature, i.e., the horizontal curve is made longer than the vertical curve. A suitable design can also be achieved by using design values well above the minimums for the design speed.

Comment: This agrees with the earlier discussion on crests and the superimposition of elements. See Figure 4(*c*) to (*e*), which show designs that are to be avoided.

• The Green Book (*2*, item 4, p. 296) continues:

> Somewhat allied to the above, sharp horizontal curvature should not be introduced at or near the low point of a pronounced sag vertical curve. Because the road ahead is foreshortened, anything but flat horizontal curvature gives an undesirable distorted appearance. Further, vehicular speeds, particularly of trucks, often are high at the bottom of grades, and erratic operation may result, especially at night.

Comment: This statement addresses the same concern as described in the section An Interesting Phenomenon. The authors suggest the following study: Using a CADD system, prepare a series of perspective drawings from the driver's viewpoint. The objective should be to determine if sag vertical curves superimposed with horizontal curves result in perspective views that make the horizontal curve appear flatter than it is in reality.

A properly designed study, as hypothesized in the section An Interesting Phenomenon, could likely determine the visual effects of varying the lengths of and overlapping the curves. If the hypothesis is true, then the situation is one in which a driver's expectancy is violated. This could lead to improper actions by drivers and, possibly, increased safety problems.

• The length of highway that can be seen at one time by the motorist should be limited, but adequate sight distance should be preserved (*1*). There should not be more than two course changes in horizontal alinement [Figure 7(*a*)] or three breaks in the vertical grade line in the view of a driver at any point [Figure 7(*b*)]. In particular, a disjointed appearance should be avoided. This may

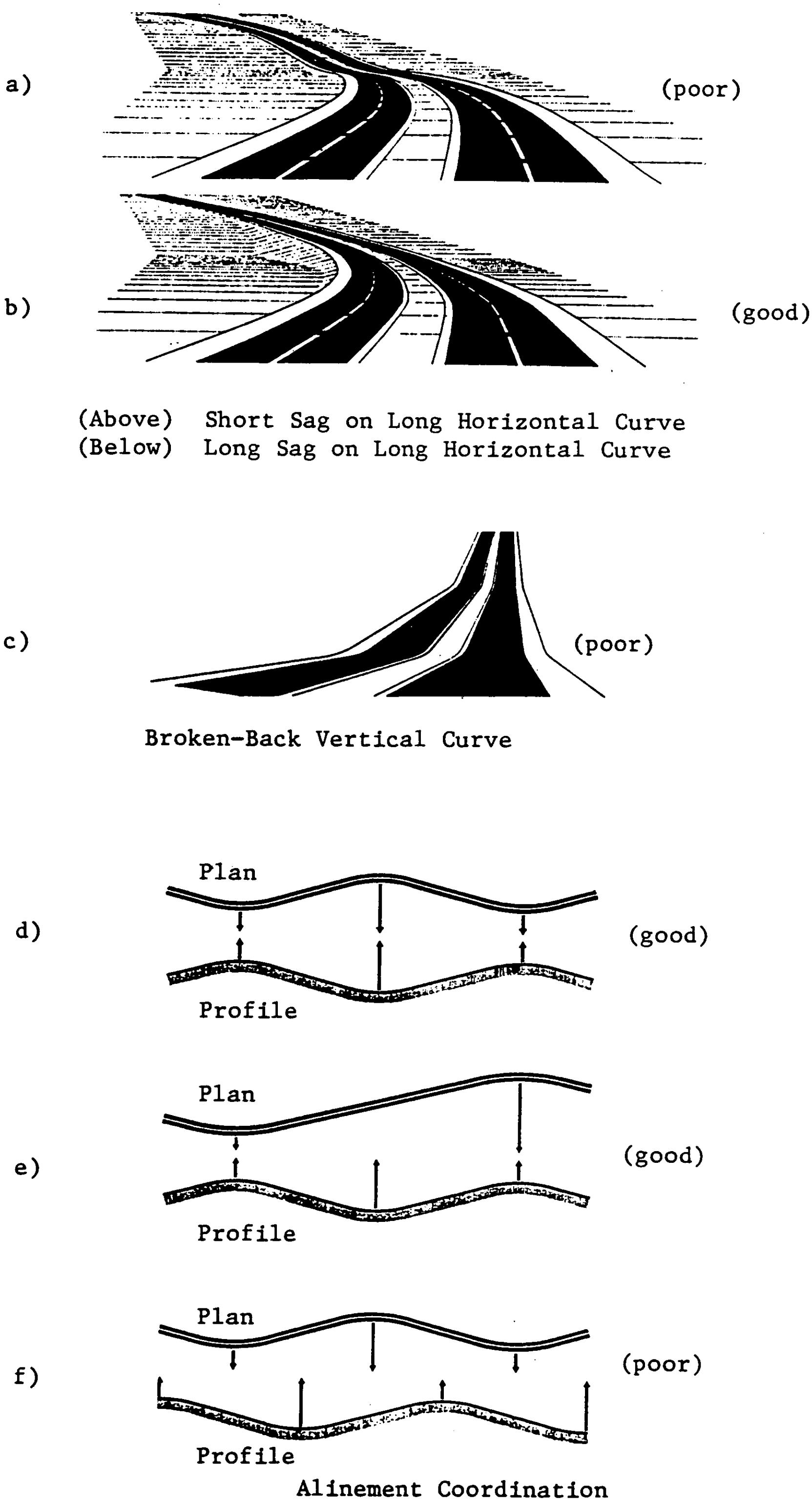

FIGURE 6 Examples of poor and good solutions, United States (*7*). (*a*) Short sag on long horizontal curve (poor); (*b*) long sag on long horizontal curve (good); (*c*) broken back vertical curve (poor); (*d*) alinement coordination (good); (*e*) alinement coordination (poor); (*f*) alinement coordination (good).

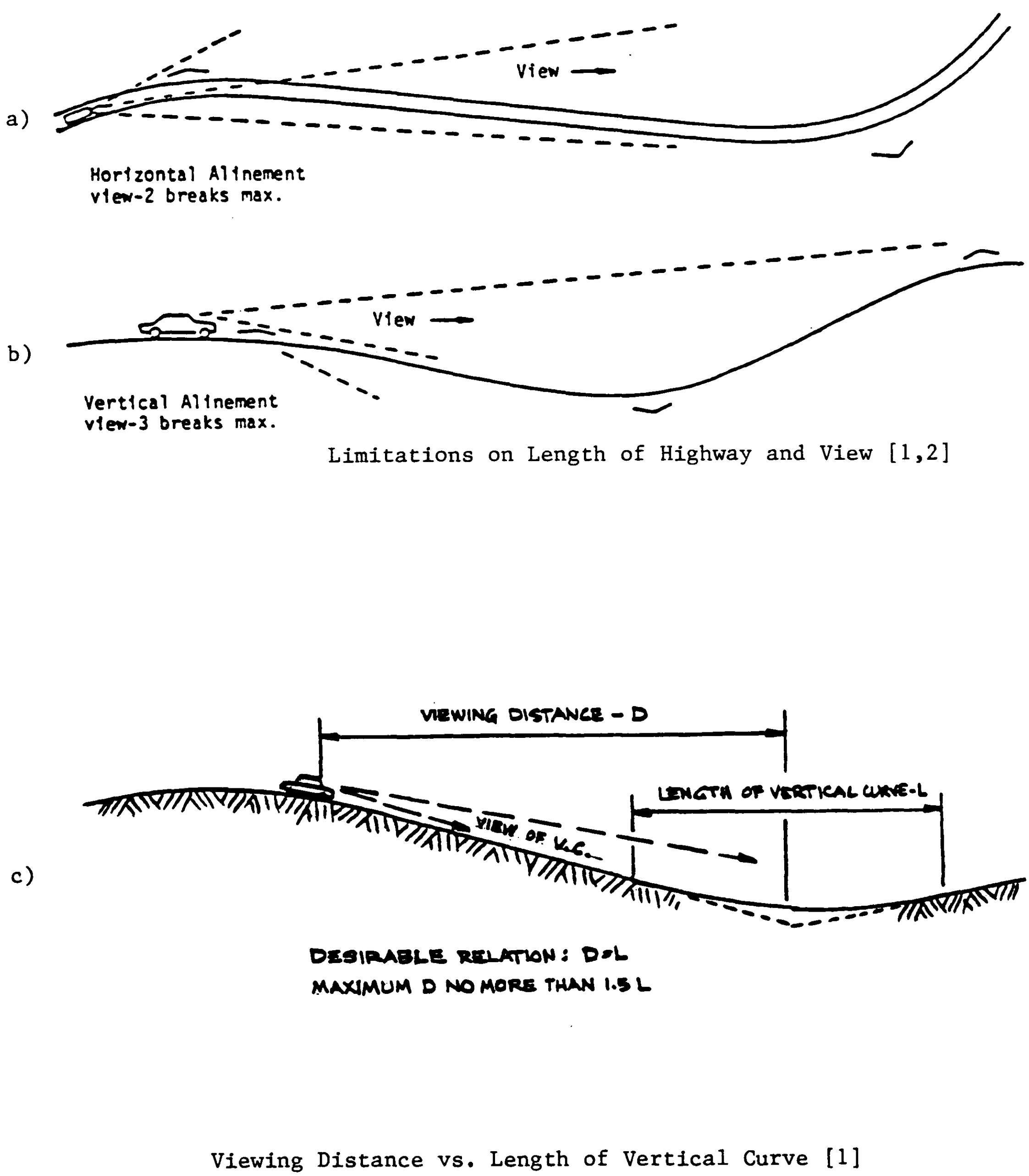

FIGURE 7 Fundamental issues for optical (visual) guidance, United States: (*a*) horizontal alinement, view: two breaks maximum; (*b*) vertical alinement, view: three breaks maximum; limitations on length of highway and view (*1,2*); (*c*) viewing distance versus length of vertical curve (V.C.) (*1*).

occur when the beginning of a horizontal curve is hidden from the driver by an intervening summit while the continuation of the curve is visible in the distance beyond (*1,2*) [Figures 4(*d*) and 4(*e*)]. It may also occur when long tangents are laid in rolling terrain such that the road appears as a series of segments of diminishing size as it passes over successive hilltops ahead [Figure 4(*f*)].

• For satisfactory appearance, curves, both horizontal and vertical, should usually be considerably longer than the minimum design standards, on the basis of safety and operational ease, would require (*1,7*). This is particularly true of sag vertical curves, which appear to the driver as sharp angles or kinks when seen from a distance. To avoid the appearance of a kink, the length of a sag vertical curve should be about the same as the viewing distance from which the curve is first perceived by the driver or, as a minimum, at least 0.6 of the viewing distance [Figure 7(*c*)]. The length of horizontal curves (in feet) should be at least 15 times the design speed of the highway (in miles per hour) and preferably twice that. [In Standard International units, the length of the curve (in meters) should be at least 3 times the design speed (in kilometers per hour) and preferably twice that length.]

Comment: The earlier discussion of vertical alinement in the section Sequence of Design Elements and Superimposition of Elements appears to support this viewpoint.

- Pushkarev (*7*) rightly claims that crest vertical curves do not pose the esthetic problems that sag curves do if they are so high that the road terminates visually on the horizon line near the crest. He makes an interesting observation that the minimum stopping sight distances [625 to 850 ft at 70 mph (*2*)] beyond which the driver does not see while going over the crest "visually often appears quite precarious, even though it is functionally safe." He implies that (a) much larger radius crest curves (generally longer crest curves) should increase the driver's feeling of safety and security and (b) a driver's feeling of safety derived from the view of the road is very important.

Comment: This agrees with the earlier discussion in the section Sequence of Design Elements and Superimposition of Elements. Perhaps someday the following will be quantifiable: (a) how to provide the driver with a feeling of safety and security and (b) the importance, in terms of safety, of such driver feelings.

SAFETY ASPECTS

General Statements

Two important considerations in highway design are design speed and sight distance. These in turn vary depending on the horizontal and vertical alinement characteristics of the highway. Favorable horizontal and vertical alinements allow for higher design speeds and extended sight distances and are expected to generally result in increased motorist safety. However, little information exists on the effects of vertical alinement on accidents. Also, although cer-

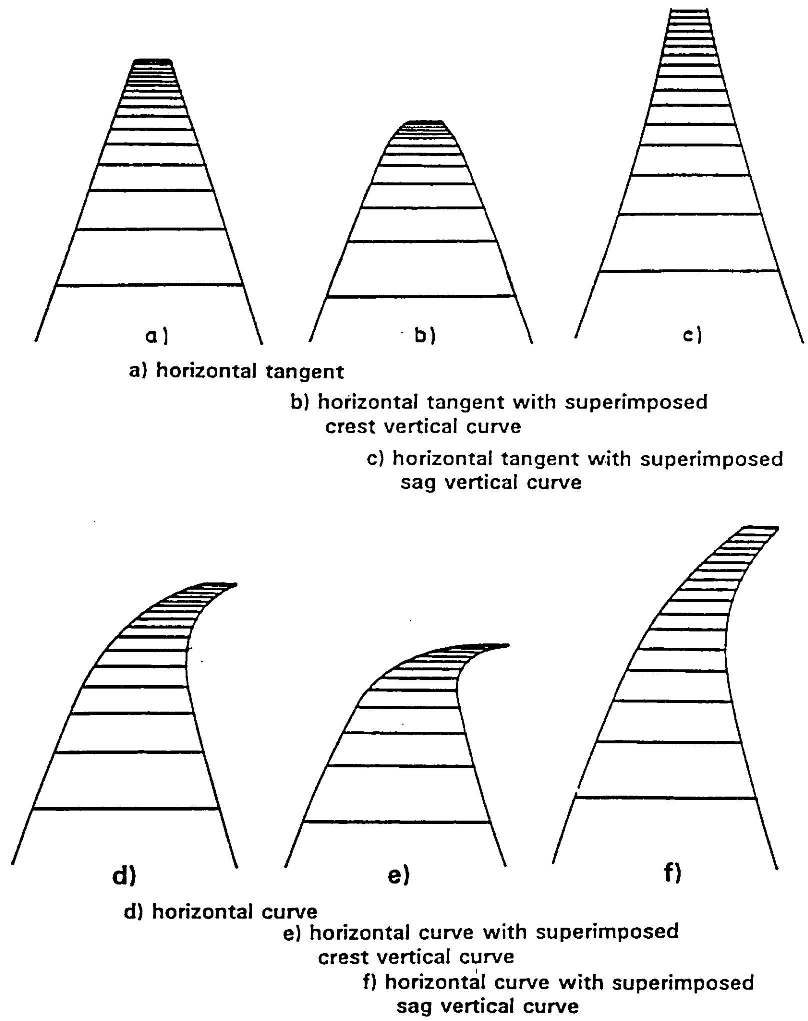

FIGURE 8 Different three-dimensional views by superimposing vertical and horizontal curves (*9*): (*a*) horizontal tangent; (*b*) horizontal tangent with superimposed crest vertical curve; (*c*) horizontal tangent with superimposed sag vertical curve; (*d*) horizontal curve; (*e*) horizontal curve with superimposed crest vertical curve; (*f*) horizontal curve with superimposed sag vertical curve.

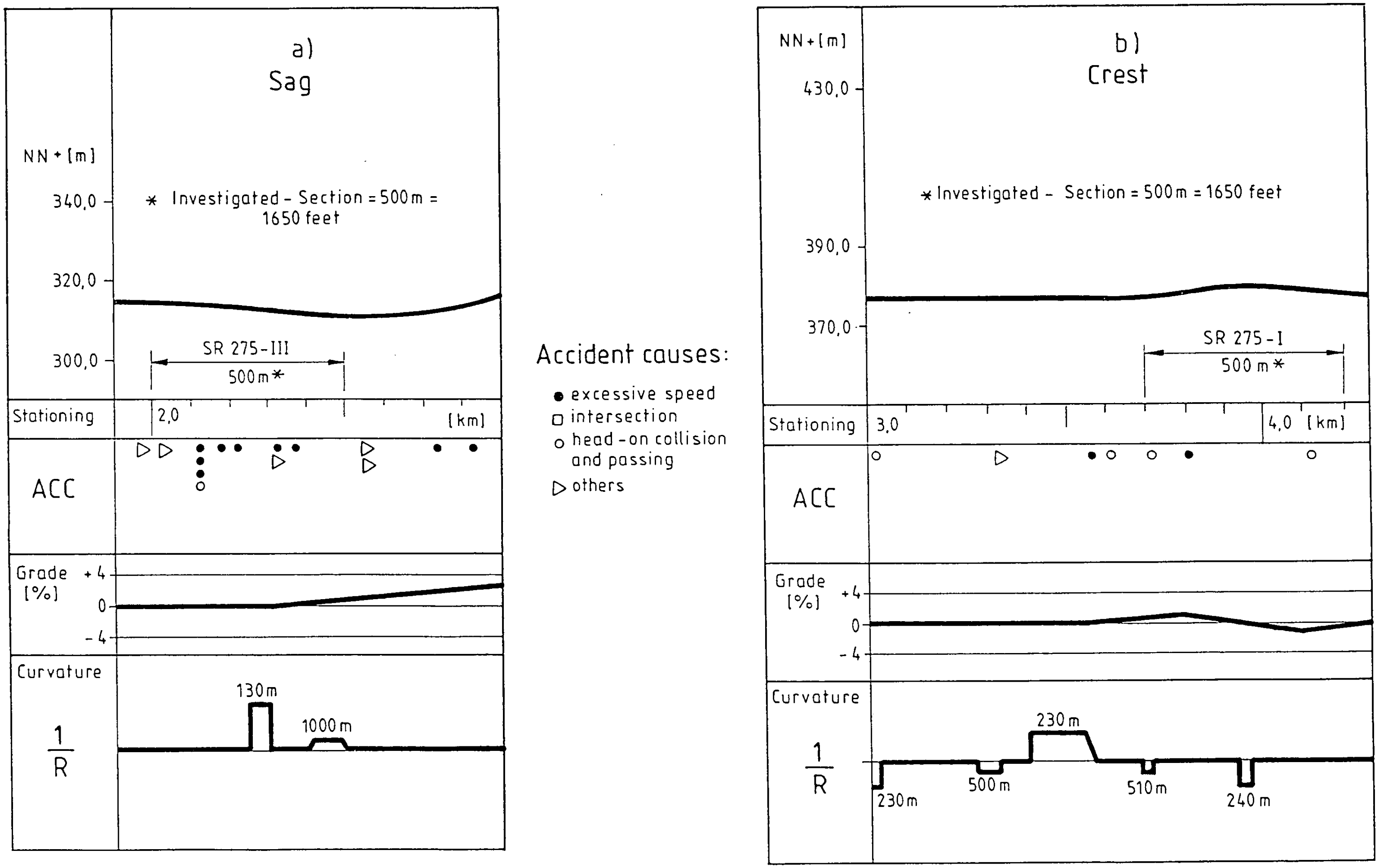

FIGURE 9 Influence on the accident (ACC) situation by the superimposition of horizontal and vertical curves: (*a*) sag and (*b*) crest.

tain combinations of unfavorable horizontal and vertical alinements are expected to increase accident frequency and severity, not much about the specific combinations of such high-accident alinements is known.

A safety evaluation process for highway geometric design was developed especially for the 1993 Transportation Research Board Conference Session Cross-Section and Alinement Design Issues and is discussed in the papers by Lamm and Smith and Lamm, et al. this Record.

Additionally, the impacts of individual design elements (like radius of curve, lane width, grade, and sight distance and their interactions on the safety aspects of a highway were analyzed in the paper by Choueiri et al., this Record. With regard to gradients, it was found for two-lane rural highways (on the basis of the present international study) that (a) grades under 6 percent have relatively little effect on the accident rate, and (b) a sharp increase in the accident rate was noted on grades of more than 6 percent.

An Interesting Phenomenon

The problems of visual perception when horizontal and vertical curves are superimposed was recognized very early in Germany (*9*). Figure 8 shows how sag and crest vertical curves change the three-dimensional view of roadways when they are superimposed with horizontal curves.

It is especially interesting to see how a vertical curve may change the perception of the curvature of a horizontal curve [Figure 8(*e*) and (*f*)]. This leads to the hypothesis that sag vertical curves superimposed with horizontal curves may result in perspective views that make the horizontal curve appear flatter than it is in reality. Therefore, in those situations higher operating speeds that could cause higher accident risks might be expected. This would be in comparison with those in horizontal curves without any superimposition of sag vertical curves. A superimposition of a crest vertical curve with a horizontal curve should reveal opposite results [Figure 8(*e*)] (*9,10*). A study of drivers' perceptions of such curve combinations by using a CADD system was recommended earlier (*2*, item 4, p. 296).

Figure 9 (*10*) shows the geometries, accident locations, and accident causes for a typical horizontal and sag vertical curve superimposition and for a horizontal and crest vertical curve superimposition. The accident rate at the sag vertical curve [Figure 9(*a*)] was 8.3 accidents per 10^6 vehicle km, in comparison with the average accident rate of 3.6 accidents per 10^6 vehicle km over the entire lengths of the observed state routes. Excessive speed was the single most frequent cause of accidents at these sites. The sag vertical curve site was especially hazardous. The 10 accidents within section SR 275-III resulted in three fatalities and three injuries. The other two sag vertical curve sites also revealed very critical results. In contrast, at the crest curve site depicted in Figure 9(*b*), there were only three accidents during the same time period. The accident rate was 1.4 accidents per 10^6 vehicle km, in comparison with an average rate of 3.6 accidents per 10^6 vehicle km. The results support the hypothesis (even if it is not statistically valid) that superimposed sag vertical curves may create a potential hazard by making the horizontal curve appear flatter than it really is.

The mathematical background and further discussion of this phenomenon can be found in an article by Osterloh (*9*). It is based mainly on human factor-related errors.

RECOMMENDATIONS

It is recommended that the following be specifically considered for inclusion in the Green Book (*2*):

1. Establishment of appropriate horizontal curvilinear alinements as described in a paper by Lamm and Smith, this Record with maximum longitudinal grades of up to 5 percent (with exceptions of 6 percent).
2. Description of the important three-dimensional design elements.
3. Increase in the use of perspective plots, which can help to detect numerous visually poor designs. This can be accomplished by using a CADD system now available in most engineering offices.
4. A brief discussion on the relationship of the rate of vertical curvature, K, to an equivalent vertical curve radius, R: R (ft) = $100K$ (feet/percent grade change) or $R = 30K$, where R is in meters.
5. Rules for ratios of horizontal to vertical curve radii (1/5 to 1/10).
6. Hilly topography, $R_{crest} > R_{sag}$; flat topography, $R_{sag} > R_{crest}$.
7. Rules for the coordination of distortion points.
8. Rules for limitations on the length of highway motorists can see.
9. Emphasizing the safety benefits of alinement coordination.

CONCLUSION

Both this paper and its companion by Lamm and Smith, this Record, present numerous indirect visual and safety-related issues. Safety aspects are especially important in the case of curvilinear alinements with grades of from 5 to 6 percent. The two papers are intended to be used together by highway designers.

The common purpose of these papers is to assist designers in avoiding horizontal and vertical designs that, in subtle negative ways, may diminish the driver's feeling of comfort, certainty, and safety and that at times may violate the driver's expectations. The proposed design guidelines should help to create highways that are much freer from operating speed inconsistencies and should reduce high-risk driving maneuvers because of errors in driver judgment. Modern geometric highway designs that correspond to the guidelines outlined in both papers would thus include more safety-related issues. However, it should be noted that some of the safety assumptions are evaluated only in a qualitative manner.

Overall, it can be concluded that many recommendations and rules for achieving good visual three-dimensional alinements (mostly on the basis of practical experience) exist. However, sound quantifiable design criteria with special emphasis on traffic safety could not be found, especially for highways where grades are greater than 6 percent. No accident analysis research work has been conducted for such grades either in Europe or in the United States. Three-dimensional alinement, a very complex component in the highway geometric design process, still represents the weakest link in the overall design of highways.

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