ANNEX IX (E)
to SWOV report
Safety effects of road design standards
R-94-7

Curves on two-lane roads

Th. Brenac
Institut National de Recherche sur les Transports et leur Sécurité, France

R-94-7 IX
Published by: SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

SWOV Institute for Road Safety Research
P.O. Box 170
2260 AD Leidschendam
The Netherlands
Telephone 31703209323
Telefax 31703201261

Notice to the reader

This volume is one of the annexes to a main report on safety effects of road design standards which was compiled by SWOV in collaboration with other European partners, in 1993-1994.

The project was carried out with financial support of the Commission of the European Union. However, no authority of the European Union has responsability for the contents of this publication.

The main report is a composition of contributions from various authors, edited by SWOV and published in both English and French. The annexes were not re-edited but were published in the form in which they were furnished by the authors. SWOV is not responsible for the contents of annexes that were produced by authors from outside the institute.

The full publication consists of the following volumes.

Main report: Safety effects of road design standards
H.G.J.C.M. Ruyters & M.Slop (ed.); SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex I: Road classification and categorization
S.T.M.C. Janssen; SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex II: Assumptions used in road design
M. Slop; SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex III: Methods for investigating the relationship between accidents, road user behaviour and road design standards
G. Maycock & I. Summersgill; Transport Research Laboratory, Crowthorne, England

Annex IV: International organizations and road design standards
H.G.J.C.M. Ruyters; SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex V: National road design standards
H.G.J.C.M. Ruyters; SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex VI: Road cross-section
L. Michalski; Technical University of Gdansk, Gdansk, Poland

Annex VII: Road design standards of medians, shoulders and verges
C.C. Schoon; SWOV Institute for Road Safety Research, Leidschendam, The Netherlands

Annex VIII: Design features and safety aspects of exit and entry facilities on
motorways in the EC (in German)
J. Steinbrecher; Aachen, Germany

Annex IX(E): Curves on two-lane roads
Annex IX(F): Virages sur routes à deux voies (in French)
T. Brenac; Institut National de Recherche sur les Transports et leur Sécurité, Salon-de-Provence, France

SAFETY EFFECTS OF ROAD DESIGN STANDARDS

CURVES ON TWO-LANE ROADS

1. INTRODUCTION

This contribution deals with the safety at curves on two-lane roads outside urban areas, and the way the road design standards take this safety aspect into account.

After a review of some research results, and considering these results, the analysis is focused on the main aspects of the geometry of the curve and its situation in the horizontal alignment. Some aspects which have been judged of less importance (superelevation,..), are considered only from the point of view of research results, but are not studied in the analysis of design standards. Only brief comments have been made on other aspects, like signing, because they do not belong so clearly to the field of road design, and because the knowledge on their effects on safety seems relatively weak. The effect of curve design on overtaking conditions is also briefly mentioned. The question of stopping sight-distance in relation with the horizontal alignment has not been treated.

2. NATIONAL AND INTERNATIONAL ROAD STANDARDS CONCERNING THE DESIGN OF CURVES : PRELIMINARY REMARKS

The most part of the national road standards, and also the international agreement AGR, contain explicit rules concerning the design of curves, in relation with the design speed. On this subject, the main elements have been already collected and described in other reports and papers (O'Cinnéide et al., 1993, Ruyters, 1993), and we will add some comments below (see point 4). Some countries have developed particular or complementary approaches, introducing, in diverse forms, the actual speeds (for example the 85th percentile of the speed distribution, obtained from a model) and/or other rules on the succession of the different elements of the horizontal alignment (see point 4).

Nevertheless, it is important to be aware of the limits of road design standards, especially in the case of curves. Both the methods and the rules are generally inappropriate to the existing roads : the alignments of a very important part of the network are inherited from the past centuries and anterior to the automotive era, and then very different from modern alignments. For example, in France, straight lines constitute 70 to 80 % of the total length of national roads (in plain environment ; 50 to 60 % in mountain environment) ; such proportions are rare in new road projects. An other limit of road standards is that they have generally been conceived principally for the main roads.

3. SAFETY AT BENDS, RESEARCH RESULTS

Some important results of the research regarding the safety at bends are reported here, but this is not an exhaustive review.

The studies which have been mentioned are generally accidents studies (some experimental studies concerning perceptive aspects or behaviour are also examined). These accidents studies are frequently of a statistical nature, based on the measurement of risks (accident rates). The factors, related to the curve design, which appear in this case should be considered as risk factors. Other accidents studies, which are called here analytical studies, are based on the detailed analysis of each accident process and its site, the accident being considered as a multi-causal and dynamic phenomenon (OCDE, 1984). In this case, the factors related to the curve design which are mentioned are causal factors having a determining influence on the accident process.

3.1. Influence of the radius of curvature

Statistical studies show that the accident rate (acc./veh.km) is high for the low values of radius, and decreases when the radius increases (e.g. : Krebs and Klöckner, 1977, Shrewsbury and Sumner 1980, Matthews and Barnes, 1988,...).

This general tendency is clear, but there are important differences between bends with the same radius, mainly due to the characteristics of upstream horizontal alignment (see below).

3.2. Influence of external factors

The alignment in which the curve take place is very important in the determination of the safety at this curve, according to several statistical studies. A british study (RRL, 1965, quoted in Kosasih, Robinson and Snell, 1987) shows that the accident rate at small radius bends is very high when the average curvature of the whole alignment is low, but relatively low when the average curvature is important (see table 1). These results tend also to show that an alignment with an important bendiness can be more safe than relatively straight alignments. Ancient results (Baldwin, 1946, quoted in Krebs and Klöckner, 1977) showed that accident rate differences between small and large radii are greatly reduced when the number of bends per kilometer increases. More recently, a model which has been obtained from (Poisson) regression shows that the accident rate at the bend is depending on two significant variables : the radius of curvature and the "easy" length on both approaches of the bend (Renault et al., 1993). This easy length is defined as the length of straight alignment or alignment with a radius of curvature larger than 1000 m preceding the bend. Its value is obtained by calculating the mean of the values measured for each approach direction. The accident rate increases when the radius decreases, and when the easy length increases.

Table 1. Relation between accident rate, radius of the curve, and average bendiness of the alignment (from : RRL, 1965, quoted in Kosasih et al., 1987).

UK non-intersection injury accidents on straights and curves on a 9 metre roadway with different levels of average curvature

Average Curvature (deg/km)	Injury Accidents/10^6 veh-km				
	Straights and Radius > 1520 m	Curve Radius (m)			Total
		610 to 1520	305 to 610	< 305	
0–25	0.7	0.7	0.6	5.3	0.8
25–50	0.6	0.6	0.6	0.9	0.6
50–75	0.4	0.3	0.6	1.0	0.5
> 75	0.2	0.3	0.6	0.7	0.4

More analytical studies give relatively converging results : Trapp (1988) shows that the main causal factor encountered on blackspots in curve is a radius smaller than the radii of the other curves on the section, and/or a more important angular change (than for other curves on the section). Yerpez and Ferrandez (1986) show that, on the french national roads, bends with a radius less than about 150 m following a straight line longer than 400 m (approximately) generate loss-of-control accidents.

Other external factors have been found : severe bend in a steep down grade, short sight-distance on the bend (during the approach) or on the end of the curve,... (Yerpez and Ferrandez, 1986, Trapp, 1988). Concerning this last point, one could note also that the radius of curvature of a circular curve of which only the first part is visible is over-estimated, i.e. that the severity of the curve is under-estimated (Virsu, 1971, Shinar et al., 1974).

3.3. Influence of internal factors

This point deals with factors, other than radius, depending on the design of the curve itself, on its own characteristics, as opposed to factors depending on the situation of the bend in its environment (including upstream alignment).

According to Yerpez and Ferrandez (1986), internal defects of design or maintenance of curves have a determining influence, on bends having a small or medium average radius of curvature (less than 250-300 m on two-lane french national roads). Several defects are frequently combined.

The main defect mentioned by these authors is the irregularity of the curvature inside the bend itself, characterized by the presence of locally very small radii compared to the average radius of the curve (see figure 1). The minimal radius is frequently reduced of more than 50 % relatively to the average radius. The irregularity of the curve has different explanations : ancient road (before the automotive era, circularity and regularity of curves were not so important), bend including several curves of same direction, bend with an excessively long transition curve (clothoid).

Other results should be considered here, especially those of Stewart and Chudworth (1990), showing that, on a few number of relatively severe bends introduced by long transition curves, the modification of bend by elimination of transition curves has resulted in important decreases of the accident numbers. Nevertheless, it is not sure that these results are entirely free from regression-to-the-mean bias. The studies of Riemersma (1989), dealing with the perception of curves, show that the presence of transition curves (of a length consistent with standards or a little shorter) deteriorates the perception of the bend and results in an over-estimation of the final radius and of the possible speed[1].

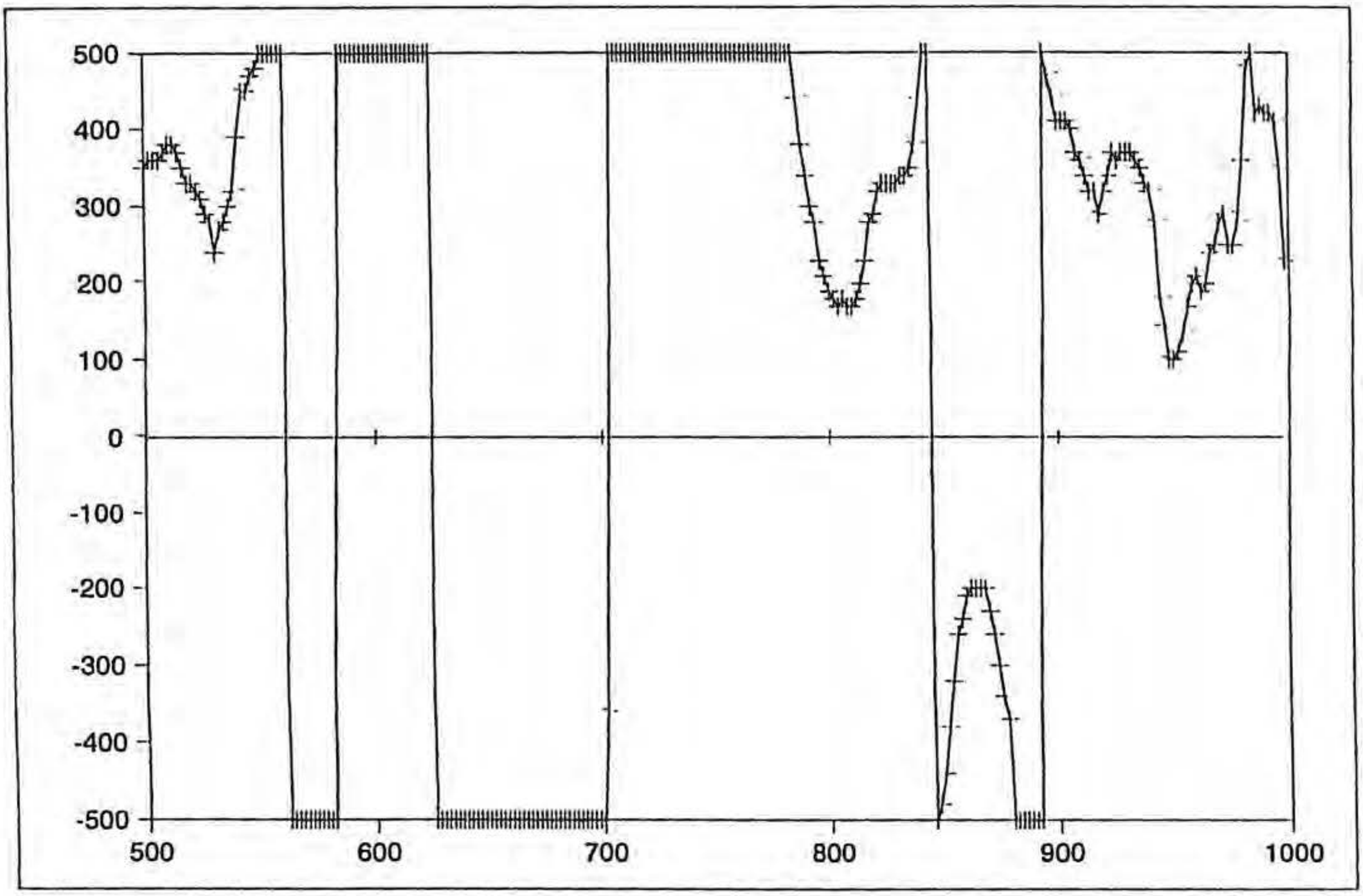
Other internal defects found by Yerpez and Ferrandez (1986) are less frequent, and are often combined with the main defect which has just been mentioned, or with a defect due to the situation of the bend in the alignment. These other defects are principally :

- poor shoulders : bad surface, presence of fixed-objects,... resulting in the impossibility of recovering manoeuvres (and in injuries) ; the statistical approach of Neuman (1984) shows also the importance of shoulders ;
- defects in surface characteristics, especially concerning the evenness of the pavement (principally the deformations with short wavelengths), and to a less extent concerning the skidding resistance.

---

[1] Nevertheless, the results of Droulez (1986-1988) show that transition curves (clothoids) may have some advantages : without clothoid, the holding of the vehicle path at the beginning of the curve seems more difficult (the subjects of the experiment, on a summary simulator, had to drive close to the theoretical path visualized by a marking) ; according to the same author, the presence of transition curve has a positive influence concerning non visual indications on the curvature variation at exit of the bend.

Figure 1. Example of the irregularity of the curvature.
The y-axis gives the value of the radius of curvature. The algebraical sign gives the direction of the bend (left or right). Radii of more than 500 m and straight lines are not distinguished. (Unpublished data from the Laboratoire Régional des Ponts et Chaussées de Lyon).



These authors have not found safety problems, such as aquaplaning, due to drainage insufficiencies. (It seems that these problems concern principally some particular points on large and rapid infrastructures, e.g. zones with superelevation change-over on 2x3 lane motorways ; Faure et al., 1991).

More generally, the effects (on safety at curves) of surface characteristics appear as less important than the effects of geometry (horizontal alignment) and roadsides (Neuman,1984).

The insufficiency of superelevation does not appear as an accident factor in the results of Yerpez and Ferrandez (detailed analysis on 800 km of french national roads), but these authors mention the negative influence of a too rapid lowering of the superelevation at the end of the curve. The insufficiency of superelevation appears as more important in the results of Trapp (investigations on blackspots sites in Germany). The statistical approach of Neuman (1984) shows that the influence of superelevation is minor compared to the effects of horizontal alignment and roadsides.

At last, in the case of small minor roads, without shoulders, the lack of visibility inside the curve (due to the vegetation, for example) has been mentioned as an accident factor, resulting in head-on collisions (the driver perceives too late the presence of another vehicle in the opposite direction and can not avoid it).(Siquot et al., 1987).

4. INTEGRATION OF SAFETY ASPECTS IN DESIGN STANDARDS CONCERNING THE CURVES

4.1. Introduction and general comments

Regarding the curves, the most part of national road "standards", and also the AGR agreement, have a sort of common basis which contains the design speed concept (or other approaching concepts) and rules concerning the minimal values of some main characteristics (especially the radius of curvature), depending on the design speed. As said above, some countries have introduced complementary rules or approaches, taking into account the actual speeds, and/or defining the conditions of the succession of the different elements of horizontal alignment.

The questions related to the design speed are treated at the point 4.2.

For detailed comparisons between countries on the main characteristics depending on the design speed, one could refer to : O'Cinnéide et al., 1993, Ruyters, 1993. I will only mention here that, for the minimal radius of curvature, which is one of the most important characteristics depending on the design speed, there is a relatively good (even if approximate) consistency between countries. For example, for the design speed 80 km/h, the comparison established by O'Cinnéide et al. between 14 countries (Austria, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Switzerland), shows that the minimal radii of curvature are comprised between 230 and 280 m, except two countries (Greece : 200 m ; Finland : 350 m). For the design speed 100 km/h, the comparison established, by the same authors, between 16 countries (the same with Sweden and United Kingdom), shows that the minimal radii are comprised between 400 and 510 m, except two countries (Greece : 350 ; Finland : 650). The values given in the annex II of the AGR agreement, are 240 m (design speed 80 km/h) and 425 m (design speed 100 km/h).

Regarding the complementary rules or approaches introduced by some countries, we have focused the analysis mainly on the road standards of three countries (Germany, United Kingdom, France), for different motives related to the developed approaches, but also to the availability of the documents, the understanding of the language, and in order that a detailed analysis would be possible. Complementary approaches introducing the actual speeds are discussed at the point 4.2. . Rules on the conditions of succession of the different elements of the horizontal alignment are discussed at point 4.3. .

Some rules related to the internal design of bends will be examined at point 4.4.

At last, the effect of the curve design on overtaking conditions is mentioned at point 4.5.

4.2. Design speed, actual speeds

4.2.1. The design speed concept

Except for some rare countries, the notions of design speed, in spite of the multiplicity of the definitions, are different expressions of the same concept.

The definitions belong generally to one of the two following families :

- the highest constant speed which can be maintained on the overall section in conventional conditions of safety and comfort, and with no limitations due to traffic, or
- the speed determining the minimal characteristics of the alignment (i.e. in conventional conditions of safety and comfort, a vehicle could negotiate the most difficult points of the alignment at this speed).

These two definitions are converging and define the same concept. This concept is either defined by the objective : the speed "offer" ensured by the infrastructure throughout the section (this is a minimal offer because at some points of the section drivers can drive more quickly) ; or defined by the mean to obtain this objective by the geometric design : the minimal characteristics of the most difficult points of the section.

Hence, the design speed appears as a level of service concept : the objective is to ensure a possible level of speed, and the safety is only a condition to be preserved. But in this design speed approach, the safety is ensured only for this level of speed, in conventional conditions (conditions of pavement surface quality, for example), and according to very summary models.

4.2.2. Problems related to the design speed concept

We will not discuss here the question to know if the simple facts to express level of service objectives in the form of speed objectives, to associate high level of service and high speed, to choose design speeds equivalent or higher than speed limits (knowing that actual speeds will be superior, on the most part of the alignment, and in the most frequent conditions) are or are not likely to contribute to the progressive and regrettable increase of the actual speeds on road networks. (cf Brenac, 1990).

The problem due to the fact that actual speeds (for example at the 85th percentile of the distribution) are locally very superior to the design speed, even in wet pavement conditions, and then that the minimal characteristics (sight-distances, for example) may be locally inappropriate has already been mentioned by Kosasih, Robinson and Snell (1987).

Concerning especially the safety at bends, one could say that the definition of a minimal radius depending on the design speed is both insufficient and unnecessarily constraining.

Insufficient in that, in the frequent case where design standards do not introduce complementary approaches (to the design speed approach), no explicit rule prevents for example from using a bend with a radius of 140 m after a straight line of 600 m, or after a serie of bends with radii comprised between 300 and 400 m, when the design speed is 60 km/h. And we know that such configurations will contribute to generate accidents (see above the research results mentioned at the point 3.2.).

On the other hand, whatever value is chosen for the design speed, the presence of a bend with a small radius, very inferior to the minimal radius, may be compatible with a good safety, if this curve is preceded and followed closely by curves with comparable or slightly larger radii, themselves introduced by compatible curves. In this sense, the minimal radius associated with the design speed is unnecessarily constraining, from a safety point of view, even if it may be justified from the point of view of the level of service (comfort, time saving,...).

4.2.3. Introducing the actual speeds : interest and limits

Three examples are developed here, by examining the road design standards from United Kingdom, Germany and France (new standards).

a) Standards from United Kingdom (TD 9/93 ; Department of Transport, 1993)

The design speed used in these standards is a speed which shall be consistent with the actual speeds expected on the alignment, and which is the basis for the design rules. The consequences of the chosen design speed for the user benefits are taken into account in the more general economic assessment of the alignment, based on cost-benefit analysis (COBA).

This design speed is determined by an iterative method : a first alignment is defined, based on a trial design speed, then actual speeds are determined from a model, and the comparison with the design speed induces if necessary to adjust some parts of the alignment or to change the design speed. One should note that the actual speed (85th percentile of the speed distribution) taken into account is a journey speed calculated on sections of rather homogeneous characteristics, with a minimum length of 2 km. The model used for the prediction of this speed is based on different variables related to the average bendiness of the section, the average visibility, the number of access per kilometre, the road type (number of lanes, type of traffic), the shoulder width,... These variables explain more than 75 % of the between site (section) variation of the journey speed (Department of Transport, 1993, 1984).

According to the UK standards, deviations relatively to the minimal values (minimal radius, for example) are possible, with different levels of deviation ("relaxations" and "departures"). Some elements given in the note TA 43/84 make then possible to estimate :

- the speed reduction induced by the sub-standards curves (based on a statistical correlation between bend speed, approach speed and radius ; the assumption is made that the approach speed is equivalent to the design speed);
- the increase of accident rate, based on a relation between accident rate and radius (but without considering the effect of the upstream alignment on the accident rate at the bend).

The standards of Denmark ("Road and pathtypes", Road directorate, 1981) give also a similar relationship for the estimation of the effects of radius on accidents.

The interest of the approach developed in the UK standards is to ensure the consistency between design speed and journey speed on a road section (at less 2 km long), based on a solid model. Nevertheless some problems are persisting : the speed may be heterogeneous, even along a rather homogeneous road section (see below at point c : 70 % of the between site variation of the speed measured on a sample of points is explained by the local characteristics of the point : radius of curvature, cross-section and gradient). Then the choice of some characteristics (sight-distance especially) may be locally inappropriate considering the level of the actual speed. One could also note that the assumption that the approach speed on the bend is equivalent to the design speed may be erroneous for the sames reasons.

At last, as we will see also at the points b and c below, the different rules related to the design speed and the actual speed modelling do not seem able to avoid some alignment inconsistencies generating important safety problems, considering the research results mentioned at the point 3.2.. This problem is may be a little more important in the case of the UK standards, because the system of multi-level deviations (relaxations and departures), very flexible, makes possible locally the use of a severe radius of curvature (relatively to the radii of the other bends on the section).

b) German standards (RAS-L1 ; FGSV, 1984)

The German standards introduce two concepts :

- the "Entwurfgeschwindigkeit" Ve, close to the design speed concept ; its choice is depending on environment and economic conditions, on the function of the road in the network, and is made considering the standards RAS-N (general design and planning of the network) and RAS-Q (cross-section) ; this speed is used to determine the minimal values of the horizontal and vertical alignment radii, and the maximal values of gradient ;
- the speed V85 (85th percentile of the speed distribution), defined on a road section, and calculated on the basis of the bendiness and the width of the road, concerning the case of two-lane (or single carriageway) roads of the A category (link function, outside urban areas); this speed, which is a journey speed on the section, is used to determine some design elements (superelevation,..) and to control the visibility conditions ; its consistency with the design speed Ve is also verified.

The design speed Ve and the speed V85 shall fulfil the following condition :

$$V85 - Ve \leq 20 \text{ km/h}$$

Else, the design speed shall be raised or the characteristics of the alignment shall be modified in order to reduce the V85 speed.

The V85 is calculated on section with a relative homogeneity regarding the bendiness. For example, a section may be 2 km long and may contain curves with diverse radii comprised between 200 and 400 m (RAS-L1, annex 1).

This V85 is given by a figure showing the relations between bendiness (unity of angle/km), road width, and journey speed.

This approach makes possible to verify that a relative consistency exists between the actual V85 speed on the section and the design speed Ve. Nevertheless, as said above, the speed may be rather heterogeneous along a section, actual speeds at a given point being heavily determined by the road characteristics at the point itself (see point c). For example, the speed in the largest curve of a section, even if this section is rather homogeneous, may be superior to the V85 defined for the section. That may induce the choice of locally inappropriate characteristics (sight-distance for example).

May be due to the fact that this approach is not sufficient to avoid some types of alignment inconsistency, the German standards contain other rules on the succession of the different elements of the horizontal alignment (see point 4.3.).

c) (Future) French standards

Although these new standards, today in way to be approved, are not official, it seems preferable to examine these standards rather than the ancient standards (not especially different from the "common basis" mentioned above, moreover). Below, "French standards" refer only to the new standards.

As in German standards, the design speed (vitesse de référence) determines only the minimal radii of curvature for horizontal and vertical alignment, and the maximal gradient. The text mentions that these minimal characteristics correspond to comfort and level of service objectives, and not to safety objectives, which are taken into account in other rules.

The actual speed at the 85th percentile is also used, but here this speed is defined at each point of the alignment. It is determined by the use of figures giving the relations between radius of curvature, road type (cross-section), gradient, and speed. The value of speed in transition areas (e.g. straight line approaching a curve) may be determined with simple assumptions concerning the acceleration and deceleration values, or using a more complex software.

The relations between geometry and speed result from the statistical studies of Gambard and Louah (1986). The sites (240 points in curves and straight lines) have been chosen in order that they are not under the direct influence of an immediately adjacent site. As said above, the local characteristics of the point (radius of the horizontal curvature, cross-section, gradient) explain more than 70 % of the between site variation. That suggests that the influence frequently attributed to the overall configuration of the alignment, for the determination of the local value of the speed, is not so important.

This V85 speed, defined in each point of the alignment, is used to verify different visibility conditions (stopping sight-distance, sight-distances at junction,...) and especially, concerning the curves, the sight-distance on the curve when approaching.

This method is not sufficient to avoid some alignment inconsistencies (see point 3.2.) and, as the German standards, this text contains other rules on the succession of the different elements of horizontal alignment.

d) Conclusion : limits of the speed-based approaches

The two following points could appear as conflicting :

- the fact that actual speeds at any point (including a point on a straight line before a curve) are heavily determined by the local characteristics of this point, and then only marginally determined by the overall configuration of the alignment (see point c) ;
- the results mentioned above (point 3.2.), especially the importance of the upstream alignment (bendiness, number of curves, radii of the bends, "easiness" of the alignment,..) in the determination of the safety at a bend.

But, in fact, these two points rather suggest that the safety problems at a bend can not be reduced to a speed problem, to an inconsistency between an approach speed and a critical bend speed, for example. In these safety problems, an important role is probably played by the driver expectancies, based on the experience of the preceding bends[2]. From this point of view, complementary rules, introduced in some standards and examined below, seem opportune.

4.3. Rules on the alignment consistency

Recommendations concerning the consistency of the succession of the different elements of the horizontal alignment are not rare in the road design standards, but they are generally imprecise and not formal. Some countries have introduced more precise rules.

The German standards contain two types of rules on this question :

- rules giving the minimal radius of a bend following a straight line ; on the category A roads (link function, outside urban areas), these rules are those given in the table 2 below ; the background of these rules seems empirical (coming from the practice : see RAL-L1 Kommentar, FGS, 1979) ;

Table 2. Minimal radius after a straight line (RAS-L1, FGSV, 1984)

Road category	Length of the straight line (m)	Minimal radius (m)
A I and A II	L > (or =) 600 m	600 m
	L < 600 m	L
A III and A IV	L > (or =) 500 m	500 m
	L < 500 m	L

- rules concerning the compatibility between the radii of two successive curves ; these rules appear on the figure 2, which defines different areas of compatibility : very good, good, acceptable, and an area of bad compatibility, which shall be avoided ; these rules refer indirectly to ancient accident studies, and are based on considerations related to the difference of speed between the two curves (see RAL-L1 Kommentar).

These rules allow certainly to detect and avoid a great number of inconsistencies. Nevertheless, some configurations which seem unsafe referring to the research results mentioned above (see point 3.2., and especially Trapp, 1988 and Renault et al., 1993) are still possible : for example the succession of a curve with a 1000 m radius, a straight line of 150 m, and a curve with a 150 m radius. But it should be mentioned that another rule, which appears only in the annex 2 of the RAS-L1, and which defines different level of compatibility between the bendiness (calculated on the 500 to 1000 m preceding the curve, according to the RAL-L1 Kommentar) and

---

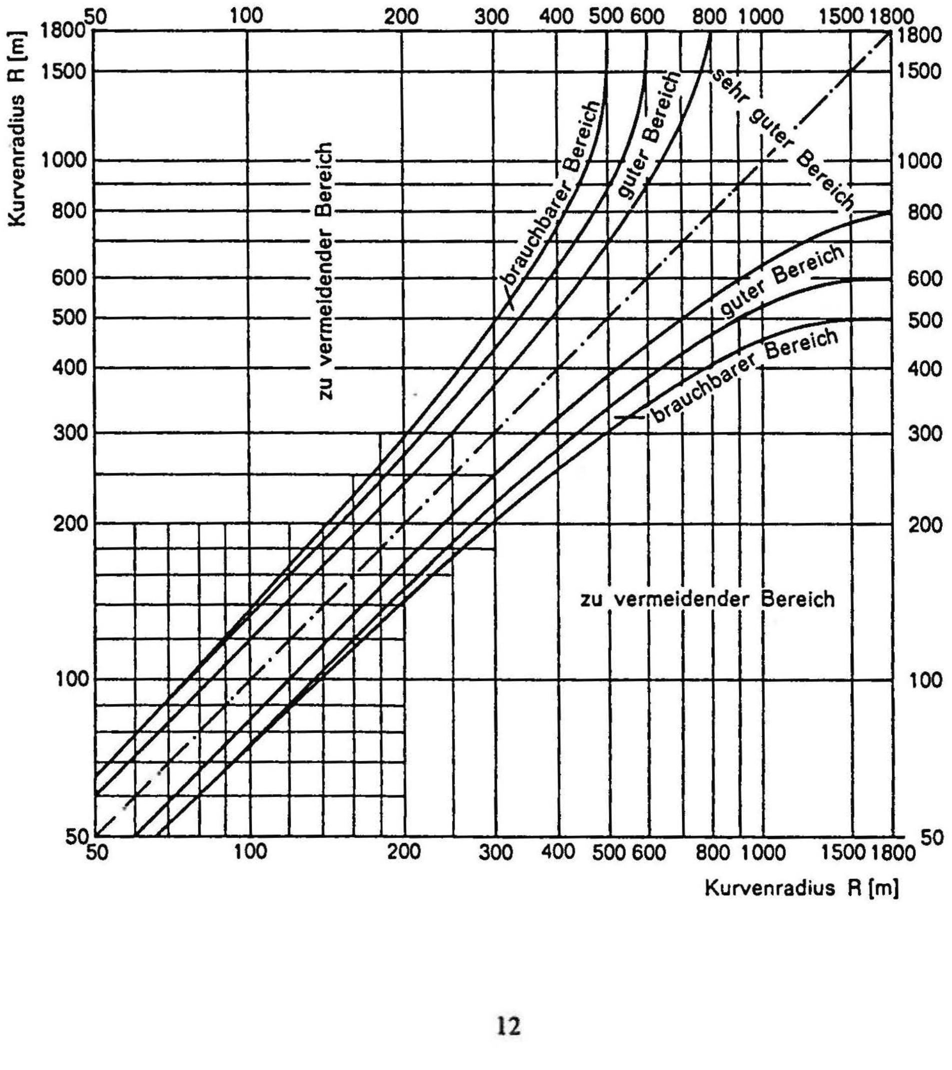
[2] For example, based on the available results concerning the actual speed in relation with geometry, the predictible speeds on approach of a curve with a radius of 150m, are nearly the same in the two following approach configurations : curve with a radius of 600m followed by a 400m straight line, or a curve with a 180m radius followed by a 400m straight line. Nevertheless, one can not exclude that the anticipation conditions are better in the second case, resulting in that the second bend (radius 150m) appears as less surprising, and generates a better and more rapid adjustment of behaviour to the encountered difficulty.

the radius of the bend, may probably avoid some configurations of this nature, but not in all cases.

It may be remarked also that the conditions for the succession of a straight line and a bend seem constraining, especially in a rather hilly environment : in this case it is probably rather difficult to have both relatively moderate radii compatible with the hilly environment and sufficiently long straight lines for ensuring a good visibility at junctions and for overtaking manoeuvres. The compliance with this rule is probably also difficult in the case of rehabilitation of an existing road with an ancient alignment, using more largely straight lines.

The elements given in the German standards concerning the compatibility between the radii of two successive curves, and concerning the compatibility between the radius of a curve and the bendiness of the preceding section, can be found also in the standards of the Netherlands (RONA, Hoofdstuk IV, DVK, Rijkswaterstaat, 1989).

Figure 2. Compatibility between the radii of two successive curves, according to the German standards RAS-L1 (FGSV, 1984).
The x-axis and the y-axis give the radii of the two curves. The figure defines several areas : in the middle, an area of very good compatibility, and, approaching the x-axis and the y-axis, an area of good compatibility, an area of acceptable compatibility and at last an area to be avoided.



French standards also contain two types of rules concerning the succession of the elements of horizontal alignment :

- rules concerning the succession of a straight line and a curve : the minimal radius of curvature after a straight line more than 500 m long is 200 m ; after a straight line more than 1000 m long, the minimal radius is 300 m[3] ; when the length L of the straight line is less than 500 m, it is recommended, but not compulsory, that the radius of the curve is superior to L/4 ;
- rules concerning the compatibility between two successive curves, even if these curves are separated by a straight line (and whatever is the length of this straight line) : the radii R_1 and R2 of these curves shall verify the relation:

$$0.67 < R1/R2 < 1.5$$

except if both R1 and R2 are superior to 500 m.

These rules are in great part adapted from different results and proposals of the researches of Yerpez and Ferrandez (1986).

The condition on the radii of two successive curves seems not very different from the condition of acceptable compatibility given in the RAS-L1 figure, but here this rule has a larger application in that it shall be verified also for curves separated by a straight line.

It is probably this fact that allows less severe rules for the succession of a straight line and a curve : for example, a curve with a radius of 120 m may follow a straight line of 400 m, what would be impossible considering the German standards, but here this straight line shall be preceded by a curve with a radius of less than 180 m, in this case, according to the relation between R1 and R2.

The choices which have been made in the French standards are probably also in relation with the will to facilitate the use of straight lines ("at less 50 % of the total length for allowing good conditions of visibility at junctions and in overtaking zones"). The French standards precise also that these conditions of consistency should be taken into consideration for the rehabilitation of existing road, in addition to the conclusions issued from the analysis of local accident data.

One could note that, differing in that from the German standards (where the circular part of the curve shall have a minimal length corresponding to 2 seconds at the design speed) no indication is given in the French standards concerning the minimal length of a curve. Then, the use of very short curves, where the vehicle paths have very large radii compared to the curve radius, could make inoperative the rules on consistency of the succession of horizontal alignment elements.

4.4. Internal consistency of a bend.

German standards recommend to avoid C-curves (two circular curves of same direction connected by two transition curves - clothoids - joined at the point of null curvature) and purely clothoidal curves (two clothoids connected at their points of maximal curvature).

---

[3] For very long straight line (5km and more, not recommended but not always avoidable, in case of tunnel, for example) other recommendations are added.

French standards exclude the use of multiple curvature bends (succession of circular curves of same direction), the use of C-curves (see above), the ovoid curves (two circular curves connected by a clothoid), the purely clothoidal curves (see above), and more generally all the complex successions of circular curves and diverse transition curves of same direction. All these configurations are considered as likely to deteriorate the perception of the curvature and to generate accidents[4].

Considering the results mentioned at the point 3.3. (especially : Yerpez and Ferrandez, 1986, Stewart and Chudworth, 1990, Riemersma, 1989), these recommendations seem to be justified.

4.5. Remark on the effect of curve design on overtaking conditions

Ensuring actual possibilities for overtaking requires always rather important sight-distance (see for example AIPCR, 1987). The use of rather large radii implies sight-distances which are frequently insufficient or dubious for overtaking, and implies a more important length of curve, and then reduces the length of straight-line (or very large curves) which would have ensured good conditions for overtaking, provided an appropriate vertical alignment.

On this base, the UK standards recommend to avoid mid-large radii, in order to provide clearly identifiable overtaking sections.

For similar reasons, the new French standards recommend to provide an important proportion of straight-line, and then to avoid mid-large or even large radii, and to define overtaking sections, combining straight line and appropriate vertical alignment.

5. SIGNING OF CURVES

As justified in the introduction, only some brief comments are made here concerning this question.

For the improvement of safety conditions at curves on existing roads, low cost measures (other than signing) are often possible when some internal defects (irregularity of curvature, too long clothoid, shoulder or pavement defects,...) have been identified. In this case, very slight amendments to the alignment (see for example Stewart and Chudworth), shoulder reconstructions, pavement treatments,..., are often sufficient. But in the other cases, low cost treatments are often limited to the signing of the curve (in a large interpretation of what is signing : signing or equipment, like bend signs, chevron boards, elements of delineation on the outer side of the curve, mandatory or advisory speed signs,...).

The positive effects of some of these signing measures appear from before-after studies (for example : SETRA, 1980), but frequently such studies have been made for blackspot treatment programs, and then they are generally biased (regression-to-mean effect). Beyond these studies, it seems there is a lack of sufficiently solid results concerning the effects of signing at curves on accidents. The cross-sectional (survey) study of Neuman (1984), which takes into account signing of curves, among other data on the curves characteristics, does not show any significant effect of signing.

---

[4] The french standards propose also an important modification of the methods and rules for calculating the length of transition curves, resulting in a strong reduction of the clothoid length relatively to the conventional values

Concerning the effect of speed signs, the (survey) study of Gambard and Louah (1986, already quoted above) does not show any significant effect of speed signs at curves on actual speeds at these sites, controling for the effects of other elements, like curvature, cross-section, gradient,...

On the outside of the curve, vertical, regularly spaced elements of delineation, of an homogeneous height, give to the driver informations directly useful for the perceptive function (estimation of distance, curvature, own speed,...). (See for example : Droulez, 1986).

But in the case where this type of delineation is provided on an entire section, and not only at curves, an increase of speed is frequently observed (for example : CETE Normandie-Centre, 1980), which implies perverse effects on safety, and a possibly negative global effect on accidents (for example : SETRA, 1982). Adverse effects are less probable when the delineation is only provided at the curves or at the most difficult curves.

The informations given by bend signs, or given by chevron boards, are of a more "cognitive" nature : they do not give elements directly useful for the perceptive estimation of curvature, distance or speed. But they suggest, beyond the bend direction, the more or less severe character of the bend. Then, it seems that their effect is very dependent on the use which is made of these signs on the road network : rare and focused on the most severe bends, they will have an important warning value for the drivers ; frequent and anarchically used for severe or more easy bends, their effect will be probably rather weak.

Based on this assumption (even if reasonable, it needs to be proved), it seems counter-productive that the practices in the different european countries are heterogeneous.

National (or international) regulations often precise elements on the design, the colour, the optical performance, the size, the position of signs. But the conditions of the use of these signs, i.e. for using or not using some signs or sign combinations depending on bend configuration and situation, are more rarely regulated.

In some countries, rules are given or suggested, for using or not using signing measures at curves. But they are different from country to country. For example, according to Rossi (1994), in Spain, there are rules concerning the use of signs : bend signs, speed signs, chevrons boards (one, two, or three) are or are not used, depending on the difference between a maximum approach speed which is obtained from assumptions on acceleration, deceleration rates, and from data on the alignment (radius of the preceding bend, distance between curves,...), and a maximum speed at which the curve may be negotiated safely, obtained considering a maximum side friction factor. In Germany, recommendations are given concerning the use of bend sign and/or chevron board, depending on the radius of the curve and the average bendiness calculated on the 500 to 1000 m preceding the curve (RAS-L1, annex 2). The standards of Netherlands (RONA, Hoofdstuk IV) also suggest to take into account the bendiness before the bend and the radius of the curve, for using some signing measures. At last, in Denmark, draft guidelines on signing and marking precise different conditions for using or not using diverse signs or equipments at curves.

For the motive mentioned above, a more homogeneous approach of this question through the different countries of Europe would be opportune. But it is probably important to remain relatively flexible : it is not sure that the need of using signing measures could be reduced to simple rules. The environment of the road, the conditions of visibility on the curve when approaching, on the end of the curve, in relation also with the vertical alignment, are probably to take into account. And the accident experience at a site can not be neglected for deciding signing measures, even if the observed accident number is not always a good guide (a relative understanding of the accident processes at the site is also important).

6. MAIN CONCLUSIONS AND PROPOSALS

Concerning the safety in the design of curve geometry, in relation with the overall configuration of the horizontal alignment, some main conclusions are summarized here :

(i) The conventional concept of design speed and the associated approach are not sufficient for ensuring the consistency of the horizontal alignment and the safety of curves.

(ii) Introducing, in diverse forms, the expected actual speeds (necessary in other respects, to verify the sight-distance conditions, for example), is positive but not sufficient to complete the conventional approach.

(iii) The introduction of consistency rules concerning the succession of the different elements of the horizontal alignment (radius of a curve following a straight line, compatibility of radii of two near curves) seems necessary from the point of view of safety. These rules are present in some national road design standards. But these rules are not homogeneous, and the corresponding knowledge are probably not sufficiently developed.

(iv) The use of complex curves containing a succession of circular curves and transition curves of same direction may generate safety problems and should be avoided. Moreover, the rules for the calculation of the length of transition curves (clothoid), that in the actual situation have a rather negative influence on the perception of the curvature and probably on the safety, should be re-analysed.

Concerning the signing of curves and its effect on safety, it seems that the research results are not still sufficient to constitute a solid back-ground for improving the standards. Concerning the use of signing in relation with the difficulty and situation of the bend, the lack of an homogeneous approach in the different countries is also to be mentioned.

Considering these conclusions, three main proposals could be made :

- it seems desirable that the national road design standards which do not contain explicit rules ensuring the consistency of the succession of the different horizontal alignment elements (minimal radius after a straight line, condition on the radii of two near curves), introduce such rules, if necessary on the base of the rules which already exist in national standards of other countries ;

- it appears, on the other hand, necessary to complete and to consolidate the knowledge on this question, especially on the relations between the characteristics of the upstream alignment[5] and the safety at the curve, in order to

---

[5] The methods and variables which can be used to describe the upstream alignment are very diverse and numerous, and only a few number of these method has been explored in the researches which have been made up to now.

obtain rules with a more solid background, which could be if necessary introduced in international texts ;

- it would be also important to develop the knowledge concerning the effects on safety of the signing of curves, to make possible more homogeneous rules through the different european countries.

REFERENCES

A.G.R. Accord européen sur les grandes routes de trafic international. Annexe II. (European Agreement on main international traffic arteries. Annex II).

A.I.P.C.R., 1987
Contribution allemande à la question IV, Routes et autoroutes interurbaines, XVIIIème congrès mondial de la route, Bruxelles, Septembre 1987.

An Foras Forbartha, National Institute for Physical Planning and Construction Research, 1977
Geometric Design Guidelines (Classification, Alignment, Cross-section). An Foras Forbartha, Dublin, Irlande.

Baldwin D.M., 1946
The relation of highway design to traffic accident experience. Convention group meetings, AASHO, p.103-109.

Brenac T., 1989 (1990)
Vitesse, sécurité et conception des tracés routiers. Recherche Transports Sécurité, n 23, septembre 1989. (in English: Speed, safety and highway design, Recherche Transports Sécurité, English issue n 5, Juin 1990).

CETE Normandie-Centre, 1980
Délinéateurs, mesures de vitesse et de trajectoires. Rapport d'étude. Centre d'Etudes Techniques de l'Equipement Normandie-Centre.

Department of Transport, 1993
TD 9/93. Departmental standard TD 9/93, Highway link design. Department of Transport, UK.

Department of Transport, 1984
TA 43/84. Departmental advice note TA 43/84, Highway link design. Department of Transport, UK.

Droulez J., 1986
Etude des indices sensoriels utilisés dans l'estimation de la courbure d'un virage. Rapport intermédiaire. Centre National de la Recherche Scientifique, Laboratoire de Physiologie Neurosensorielle, Paris.

Droulez J., (approx. 1988)
Analyse des indices sensoriels impliqués dans la perception de la courbure des virages. Rapport final. Non daté, vers 1988. Centre National de la Recherche Scientifique, Laboratoire de Physiologie Neurosensorielle, Paris.

D.V.K., Rijkswaterstaat, 1989
Richtlijnen voor het ontwerpen van niet-autosnelwegen (RONA), Hoofdstuk IV, Alignement. D.V.K., Rijkswaterstaat, Rotterdam, NL.

Faure B., Verhée F., Lucas J., 1991
Techniques nouvelles de couches de roulement. Les enrobés drainants. Bulletin des Laboratoires des Ponts et Chaussées, n 172, Mars-Avril 1991.

FGS, 1979
RAL-L1 Kommentar. Kommentar zu den Richtlinien für die Anlagen von Landstrassen, Teil Linienführung, Abschnitt Elemente der Linienführung, Ausgabe 1973. Forschungsgesellschaft für das Strassenwesen, 1979.

FGSV, 1984
RAS-L1. Richtlinien für die Anlage von Strassen, Teil Linienführung, Abschnitt 1 : Elemente der Linienführung. Forschungsgesellschaft für Strassen- und Verkehrswesen, 1984.

Gambard J.M., Louah G., 1986
Vitesses pratiquées et géométrie de la route. SETRA.

Kosasih D., Robinson R., Snell J., 1987
A review of some recent geometric road standards and their application to developing countries. TRRL, report n 114.

Krebs H.G., Klöckner J.H., 1977
Untersuchungen über Unfallraten in Abhängigkeit von Strassen- und Verkehrsbedingungen ausserhalb geschlossener Ortschaften. Forschung Strassenbau und Strassenverkehrstechnik, Heft 223, 1977.

Matthews L.R., Barnes J.W., 1988
Relation between road environnment and curve accidents. Proceedings of the 19th Conference of the Australian Road Research Board, Canberra, Aug.-Sept. 1988.

Ministerio de Obras Publicas y Urbanismo, Direccion General de Carreteras, 1990
Instruccion 3.1-1C/1990 "Trazado", Ministerio de Obras Publicas y Urbanismo (SP).

Neuman T.R., 1984
Discriminant analysis as a tool for investigating highway safety relationships. I.T.E. Journal, oct. 1984.

O.C.D.E., 1984
Programmes intégrés de sécurité routière.

O'Cinnéide D., McAuliffe N., O'Dwyer D., 1993
Comparison of road design standards and operational regulations in EC and EFTA Countries. Commission des Communautés Européennes, Programme R&D Systèmes télématiques dans le domaine des transports.

Renault J., Deuss C., Chambon A., Gallen C., 1993
Statistique appliquée. Etude des accidents en virage sur route nationale. ENSAE, SETRA, non publié / unpublished.

Riemersma J.B.J., 1989
The effect of transition curves and superelevation on the perception of road-curve characteristics. TNO report. TNO, SWOV.

Road Directorate, 1981
Road and pathtypes, catalogue of types for new roads and paths in rural areas. The Road Directorate, the Technical Committee on Road Standards, Denmark.

Rossi S., 1994
Signing and marking of curves in Spain. (Non publié, adapté de documents de recommandations espagnols / unpublished, adapted from Spanish guidelines).

RRL, 1965
Research on road traffic. London : HMSO. Road Research Laboratory. (Cité par / quoted in Kosasih et al., 1987).

Ruyters H., 1993
Established international road design standards. Contribution to the 1st workshop "Research on safety effects of road design standards". SWOV, Leidschendam, 1-2 July 1993.

SETRA, 1980
Points noirs glissants. Bilan des accidents sur les aménagements réalisés. Rapport d'étude. SETRA.

SETRA, 1982
Eléments non publiés sur le suivi de la sécurité après équipements d'axes (Unpublished elements on the safety assessment of equipment of road sections).

SETRA, Ministère des Transports, 1993
Aménagement des routes principales (ARP). Document provisoire. SETRA, Ministère des Transports (F).

Shinar D., McDowell E.D., Rockwell T.H., 1974
Improving driver performance on curves in rural highways through perceptual changes. Ohio State University.

Shrewsbury J.S., Sumner S.L., 1980
Effects on safety of marginal design elements. Proceedings of the PTRC seminar in Warwick, 7-10 July 1980. PTRC.

Siquot C., Brenac T., Aubin H., Decamme C., 1987
La sécurité des routes secondaires. SETRA.

Stewart D., Chudworth C.J., 1990
A remedy for accidents at bends. Traffic Engineering and Control, Feb. 1990.

Trapp K.H., 1988
Analyse und Beseitigung von Unfallstellen in ausserörtlichen Strassennetz, communication à la conférence internationale "Roads and Traffic 2000", Berlin, Sept. 1988.

Virsu V., 1971
Underestimation of curvature and task dependence in visual perception of form. Perception & Psychophysics, 1971, 9, 339-342.

Yerpez J., Ferrandez F., 1986
Caractéristiques routières et sécurité. Synthèse INRETS n 2. INRETS.