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Methods for ensuring consistency of horizontal alignment elements

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Subject review

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On rural two lane roads, which form over 80 percent of the total road network in most countries, most accidents are caused in curves. The most frequent cause of accidents is the inconsistency of horizontal alignment elements with respect to possibility of maintaining the desired speed of travel. An overview is given of existing methods and latest research, as related to the evaluation of vehicle operation speeds, and consistency of horizontal alignment elements on rural two lane roads. Advantages and deficiencies of guidelines applied in individual countries are also presented.

Key words:
design speed, vehicle operation speed, route flow consistency, cross slope, coefficient of radial resistance to friction

Pregledni rad

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Metode za osiguranje konzistencije toka trase

Na izvangradskim dvotračnim cestama, koje u većini zemalja čine više od 80 % ukupne duljine cestovne mreže, najveći se broj nesreća događa u krivinama. Najčešći je uzrok nesreća nekonzistentnost elemenata trase s obzirom na mogućnost održavanja željene brzine. U radu su izložene postojeće metode i najnovija istraživanja vezana za procjenu operativnih brzina i osiguranje konzistencije elemenata horizontalnog toka trase na izvangradskim dvotračnim cestama te su opisane prednosti i nedostaci smjernica pojedinih zemalja.

Ključne riječi:
projektna brzina, operativna brzina, konzistencija toka trase, poprečni nagib, koeficijent radijalnog otpora trenja

Übersichtsarbeit

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Methode zur Sicherstellung der Konsistenz des Trassenverlaufs

Auf den außerstädtischen zweispurigen Straßen, die in dem Großteil aller Staaten über 80% der Gesamtlänge des Straßennetzes ausmachen, finden die meisten Unfälle in den Kurven statt. Die häufigste Unfallursache ist die Inkonsistenz der Trassenelemente bezüglich der Möglichkeit der Beibehaltung der gewünschten Geschwindigkeit. In der Arbeit wird eine Übersicht der bestehenden Methoden und neuesten Forschungen bezüglich der Schätzung operativer Geschwindigkeiten und der Konsistenzsicherstellung der Elemente des horizontalen Trassenverlaufs auf außerstädtischen zweispurigen Straßen gegeben. Ferner werden die Vor - und Nachteile der Richtlinien einzelner Staaten angeführt.

Schlüsselwörter:
Projektgeschwindigkeit, operative Geschwindigkeit, Konsistenz des Trassenverlaufs, Querneigung, Koeffizient des radialen Reibungswiderstands

1. Introduction

A good road design involves selection of such alignment elements that allow constant driving speed along the selected route, thus providing for efficient, comfortable and safe travel. The greatest safety problem in the design of rural two-lane roads is the choice of geometric elements of horizontal curves where more than 50 % of accidents actually occur [1]. Baldwin [2] shows that while the accident rate increases as the radius of horizontal curves decreases, the accident rate for small radius curves decreases as the frequency of curves (per length of highway) increases. This shows that there is a connection between the traffic safety and consistency of the road elements. Proper consistency ensures that successive road elements provide for uniform driver behavior in line with his expectations [3]. Driver behavior includes information processing and decision-making processes affected by his expectancy which is, according to [4], the tendency of drivers to react to what they expect rather than to the real traffic situation [3]. Nataneen and Summala [5] suggest that the expectancies are related to the passage of time, i.e. that expectancies are more strongly influenced by more recent experience than by less recent experience. This for instance means that, after a few large radii, the drivers expect that the radius of the next curve would also be large. Therefore, the consistency of alignment elements ensures safe driving conditions at the desired speed on the entire road segment, while the inconsistency is manifested when drivers must slow down below the desired speed to safely connect to the next road element. So, the inconsistency implies higher likelihood that an accident will actually occur. Speed studies on roads with the design speed of less than 100 km/h [6, 7] show that the average speed and the 85 % speed in curves, are generally higher than the design speed. This problem is especially evident in situations when sharp curves follow large radius curves because the travel speed greater than the design speed results in side friction that is considerably above the design value. Furthermore, for curves with radius above the minimum one, it is necessary to determine an optimum distribution of superelevation and side friction values in accordance with operating speeds. National guidelines significantly differ as to the methodology of design speed selection. The choice of unrealistically small design speed values results in an insufficiently high superelevation selection, and so the side friction needed to maintain turning motion is greater than the driver would expect. This can make the driver hesitant, leading him to activate the brake, which activates the friction component in longitudinal direction, i.e. reduces the available side friction and increases the possibility of skidding out of the roadway. In addition to design consistency, a good road design must also establish a proper balance between the superelevation and side friction values in curves, and actual driving speeds. This paper presents an overview of design methods for two-lane rural roads in terms of speed, superelevation and side friction consistency.

2. Design values for speed, superelevation and side friction

2.1. Design speed

The design speed concept is the basis of all geometric design guidelines. According to this concept, the design speed is determined based on the road and terrain category. It is used to determine minimum values of road alignment elements, among which the most important one is the determination of minimum radius of horizontal curves.
The minimum radius of horizontal curvature R_{min} (m) for a design speed V_p (km/h) is determined from the equation of vehicle stability in curve for the maximum permissible superelevation q_{max} (%) and the side friction factor of f_{Rdop} :

$$R_{\min} = \frac{V_p^2}{127(q_{\max} + f_{Rdop})} \tag{1}$$

In this way, the safe driving speed is provided in curves with minimum radius, while road segments with flatter curves allow for higher driving speeds. Most guidelines recommend that minimum radii be applied in exceptional situations only, and designers are encouraged to adopt higher speeds. Subsequentelly, alignments based on the design speed concept may generate operating speeds that fluctuate considerably along different road sections, especially if guidelines which define no upper limit value of curve radii are applied. Speed variability has been the cause of many accidents. Studies [8, 9, 10] show that accident rates at curves with small radii are up to 5 times higher when compared to accident rates on straight road sections.
Since it has been established that the design speed concept has a lot of deficiencies, many researchers in different parts of the world have conducted over past decades numerous investigations focusing on the relationship between the design and the actual (operating) speed in curves. This research resulted in inclusion of the operating speed in the design process.

2.2. Operating speed

The operating speed is usually taken as 85 percent of the speed distribution at a particular road segment, i.e. it is the speed below which 85 percent of drivers actually drive. The inclusion of operating speed in the design procedure allows estimation of speed changes between adjacent road elements, as well as a more realistic determination of superelevation values in large radius curves. Many factors affect the free flow speed of vehicles. The most investigated ones are: physical characteristics of the road, weather conditions, and speed limit. It has been established that radii of horizontal curves have the greatest impact on the free-flow speed of passenger cars. This free flow speed is much less influenced by the grade, radius of curvature, vertical alignment, and cross section. The most recent overview of operating speed models applied in various parts of the world is given in [11]. Several studies have shown that the free speed in curves R<500 m is mostly influenced by the road curvature and approach speed (i.e. speed at which vehicle approaches a curve), as shown in Figure 1. This figure shows that, for the same values of curve radius, the 85 % speed in curve differs significantly depending on the speed at which drivers approach the curve. Thus for the radius of 120 m, the 85 % speed changes from 50 to more than 80 km/h depending on the approach speed (60 to 100 km/h).

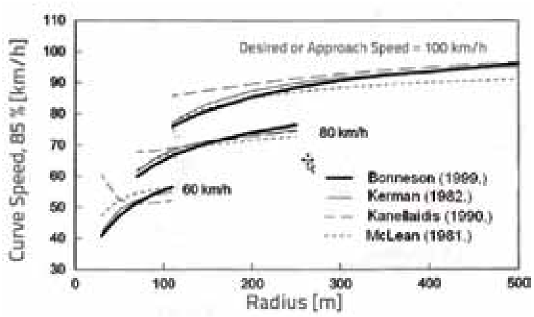

Figure 1. Relationship between the operating speed, curve radius, and approach speed [12]

2.3. Superelevation

The superelevation is directed toward the centre of horizontal curve to support the turning motion. There are practical upper limits for superelevation in horizontal curves. The limiting values are related to weather conditions (frequency and quantity of snow and ice), adjacent land use (urban or rural roads), and the percentage of slow vehicles. Most European countries apply maximum superelevation rate of 7 % for rural roads. In Germany [13], the minimum radius of curvature is calculated using the superelevation value of 7 %. However, as the operating speed exceeds the design speed, German guidelines apply the superelevation of up to 8 % in sharp curves in order to reduce the resulting side friction. On the other hand, USA guidelines [14] allow the use of five different maximum superelevation values: 4, 6, 8, 10 and 12 %, in keeping with conditions prevailing in various states of the USA The values of 10 and 12 % are applied in warmer climates, the values of 6 and 8 % in areas with frequent occurrence of snow and ice, while the limiting values of 4 to 6 % are used for roads in urban areas.

2.4. Side friction factor

Side friction limiting values used in the USA guidelines are based on research campaigns conducted more than 70 years ago, which were based on driver comfort [15]. These values range from 0.17 for the speed of 20 km/h to 0.09 for for the speed of 120 km/h.

The practice in European countries greatly differs from that applied in the United States. Thus, numerous measurements of tangential friction factors, for various pavement conditions, were made in Germany and diagrams of limiting friction (skidding) values f_{Tmax} as a function of speed were developed. The value of f_{Tmax} is determined based on the 95 % percentile of the distribution of all recorded skidding values of friction. When one drives in a curve, the lateral component of the friction is also activated, and hence the available values of tangential friction are reduced. Therefore, the design (permitted) value of tangential friction coefficient is:

$$f_{Tdop} = \sqrt{f_{T\max}{}^2 - f_{Rdop}{}^2} \qquad (2)$$

The maximum side friction factor is the value established when the skidding starts. For safety reasons, the design values are much lower than the limiting values, calculated according to:, $f_{Rdop} = n \cdot 0{,}925 \cdot f_{Tmax}$ where 0.925 represents the ratio of maximum available friction in the radial and tangential directions due to tire characteristics, and n is the utilization ratio of the available friction. For rural roads, n is 0.5, which ensures that 89 % of the total friction remains available in the tangential direction. The same principle is applied in Croatia, but it is based on older German regulations in which the coefficient n amounted to 0.6.

This side friction factor value is sufficiently small compared to the limiting (skidding) value, but is still large enough to make the drivers feel a slight discomfort as a "warning" advising them not to accelerate. Although the USA and European approaches for determining the lateral friction design values significantly differ from one another, the design side friction values for rural roads with speeds greater than 70 km/h are quite similar (Figure 2).

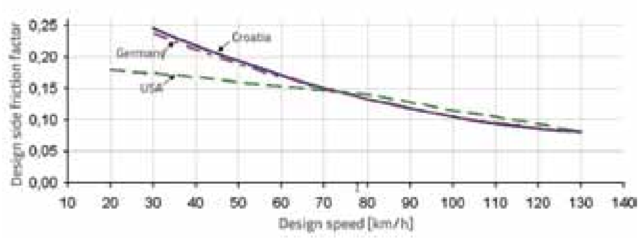

Figure 2. Maximum design side friction factors recommended by several highway agencies

3. Design guidelines for horizontal alignment

This section provides an overview of design guidelines for horizontal alignment, as applied in various countries, and possible consequences of their application.

3.1. United States of America (USA)

According to the USA guidelines [14], the design speed is determined based on the road category, topography and land use in areas through which the road passes. Design elements determined according to the design speed concept are considered as minimum values, and designers are encouraged to adopt higher values. Minimum values are used in exceptional situations only. This design approach may lead to alignments with abrupt changes between successive elements. Thus driving speeds are likely to exceed the design speed on most parts of the alignment. Although the guidelines rely on the assumption that drivers will respect the speed limit, some studies [16] have shown that drivers adjust speed according to geometric characteristics of the road, while disregarding the speed limit. In his paper [3], Krammes gives a critical review of methods for the selection and application of design speed with respect to the research results presented in [6, 7], and concludes that the concept of design speed can ensure the operating speed consistency only when the design speed is greater than the desired speed of most drivers, which is not ensured by the application of the guidelines. The observed difference between the operating speeds and design speeds points to the following deficiencies of the current methodology:

1. Design speed applies only to curves, not the tangents, as there are no criteria for determining their length,
2. Designers are encouraged to design curves with radii larger than the minimum one, which results in operating speeds that are significantly higher than the design speed,
3. There are no measures to ensure alignment consistency, except for the superelevation distribution in curves.

USA guidelines define five methods for the distribution of superelevation and side friction factor in curves, as a function of road and traffic conditions (Figure 3).

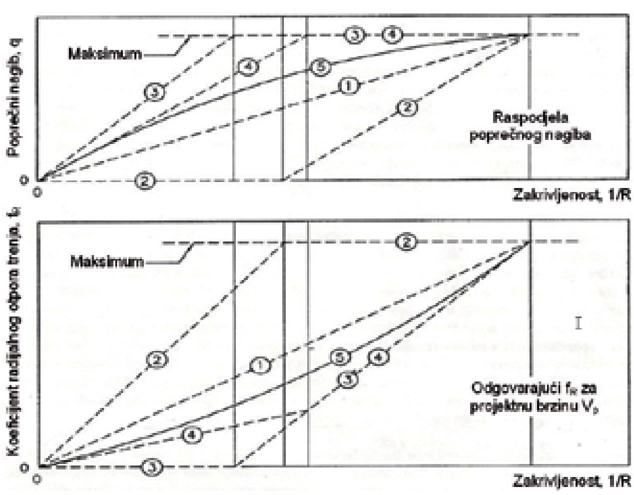

Figure 3. Methods for the distribution of superelevation and side friction [14]

According to Method 1, the superelevation and side friction are directly proportional to the inverse of the radius (1/R). This method would be ideal for driving at constant speed along all road elements, which is not the case. Under free flow conditions, a higher superelevation would be better for vehicles exceeding the design speed in milder curves, as that would ensure a greater driving comfort. However, smaller superelevations would be more advantageous for vehicles in peak hours when the operating speed is smaller than the design speed, as development of the negative lateral force would thus be avoided.

This non-uniformity of speed distribution has lead to the development of other methods: Method 2, which is suitable for urban areas where driving speed is variable, and Method 3, which is appropriate for rural roads. The Method 2 uses side friction to sustain all lateral acceleration up to the curvature corresponding to the maximum side friction factor, and this maximum side friction factor is available on all sharper curves. No superelevation is needed in flatter curves where less than the maximum side friction is needed. When the superelevation is required, it increases rapidly as curves with maximum side friction factor grow sharper.

In milder curves, the Method 3 applies superelevation without side friction until the maximum is reached, and then in sharper curves, the friction increases linearly with an increase in curvature. This method used to be applied for rural roads because it provides for comfortable ride in larger radius curves. However, when this method is applied on roads with low speeds, it causes development of negative friction during peak hours. This is why the Method 4 was subsequently developed. It differs from the Method 3 by distribution of f_R and q values, which is related to operating speed.

The Method 5 is nowadays used in the design of rural roads. This method is a compromise between the Methods 1 and 3 (4) in that the greater superelevation values are applied even in mild curves, while the side friction factor increases rapidly in sharp curves. It results in a parabolic distribution of superelevation and side friction factor as shown in Figure 3.

The Method 5 takes into account the fact that drivers on rural roads drive at speeds higher than the design speed in milder curves. The deficiency of guidelines in terms of speed consistency is partly compensated by the use of larger superelevation values. Although numerous studies in the USA confirm the need to make amendments to the guidelines, this has still not been done.

3.2. Europe

The design approach ensuring high level of consistency, based on assessment of vehicle operating speed, has been adopted in many countries. German researches were the first ones to introduce the operating speed concept when they were making their guidelines [13] for the year 1973. In these guidelines, the operating speed has become a criterion for the design of road elements. This was the first time that actual parameters have been included in the design process. Over the last decade, many German researchers attempted to determine dependency between the operating speed and road characteristics (Dilling, Lamm, Trapp, Oellers, Koeppel, Bock, Kassar, Biederman, Lippold, Bakaba). Some of these authors place emphasis on estimation of operating speed on homogeneous road sections, while others estimate speed on individual road elements (curves, tangents). Over the last four decades, the largest number of studies was performed by Lamm. Results gained in his research have been used in road design guidelines applied by many European countries, including Croatia. All German design guidelines for horizontal alignment (editions: 1973., 1984. and 1995) [13] were made based on the results of his research. A brief outline of international studies [17] conducted by Lamm, in which safety criteria for achieving consistency are proposed, is given in this paper. These criteria relate to:

- Design consistency
- Operating speed consistency
- Driving dynamics consistency

Limiting values of these criteria are given in Table 1. The Criterion 1 refers to the adjustment of certain elements so that the absolute difference between the design speed V_d and operating speed V_{85} would remain within certain limits at each element (10 km/h in good area, 20 km/h in acceptable area). The Criterion 2 requires that the operating speed at adjacent elements remains within certain limits. According to Criterion 3, the actual value of side friction, f_R (due to operating speed) should not be significantly greater than the allowable design value, f_{Rd} (defined for the design speed).

Different expressions have been developed for operating speed based on research conducted in many countries (USA, Lebanon, Greece, Australia, France). All expressions take into account the dependence of operating speed on road curvature. The equation based on research conducted in Germany is presented below:

$$V_{85} = \frac{10^6}{(8270 + 8{,}01 \cdot KK)} \qquad (3)$$

Where CCR_s is the curvature change rate:

$$KK = \frac{\left(\frac{D_{KL}}{R} + \frac{L_1}{2R} + \frac{L_2}{2R}\right) \cdot 63700}{L} \ \text{(grad/km)} \qquad (4)$$

where

$D = D_{KL} + L_1 + L_2$ - length of curve (km))

D_{KL} - length of circular curve (m)

L_1, L_2 - length of clothoids (m).

Operating speeds between adjacent elements, and the relationship to the design speed (criteria 1 and 2), can be calculated and compared using the expression (3). The diagram of the relationship between radii of adjacent curves, shown in Figure 4, was made based on the criterion 2. The equation (3) was used for calculating the 85% speed. For acceptable values of speed difference between adjacent curves, acceptable adjacent curve radii were calculated according to equation (1). Based on the traffic safety study presented in [18], the expected accident rate in smaller radius curves is at least two times greater for curves situated in fair area, when compared to curves in good design area. Therefore, it is recommended in [17] that the use of fair area be avoided on new roads for curves with R<200 m.

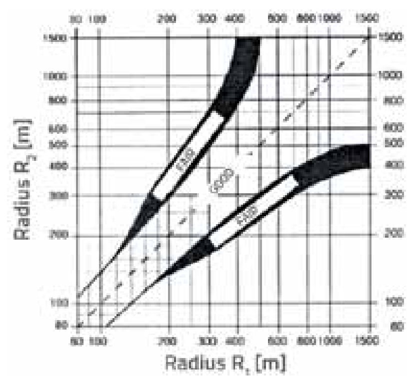

Figure 4. Relationship between adjacent curve radii [13]

The same criteria were used to determine the relationship between the tangent segment length and curve radius.

Expressions (3) and (4) are not directly used in 1995 guidelines for calculating the operating speed. In fact, two diagrams are used instead of these expressions. The diagram shown in Figure 5a is used to estimate the operating speed on homogeneous road segments of new roads. The diagram in Figure 5b shows an estimated operating speed in a single curve. It is used to evaluate consistency on existing roads.

Alignments of new (planned) roads are divided into sections with constant curve values: $K = \sum_i \frac{\gamma_i}{L}$ (gon/km or degree/

Table 1. Ranges of safety criteria [17]

Safety criterion	Good	Fair	Poor
Criterion 1	$\lvert V_{85}^i - V_p \rvert \leq 10\ km/h$	$10\ km/h < \lvert V_{85}^i - V_p \rvert \leq 20\ km/h$	$20\ km/h < \lvert V_{85}^i - V_p \rvert$
Criterion 2	$\lvert V_{85}^i - V_{85}^{i+1} \rvert \leq 10\ km/h$	$10\ km/h < \lvert V_{85}^i - V_{85}^{i+1} \rvert \leq 20\ km/h$	$20\ km/h < \lvert V_{85}^i - V_{85}^{i+1} \rvert$
Criterion 3	$0{,}01 \leq f_{Rdop} - f_R$	$-0{,}04 < f_{Rdop} - f_R \leq 0{,}01$	$f_{Rdop} - f_R < -0{,}04$

km), where γ_i is the directional angle of the curve i (gon or degree), and L is the section length (km). Then the operating speed (85 %) is estimated as a function of the average CCR from the diagram shown in Figure 5a. Once the operating speeds are determined for each section, they are compared to determine possible inconsistencies. For existing roads, the operating speed is estimated with respect to the radius of curve according to Figure 5b.

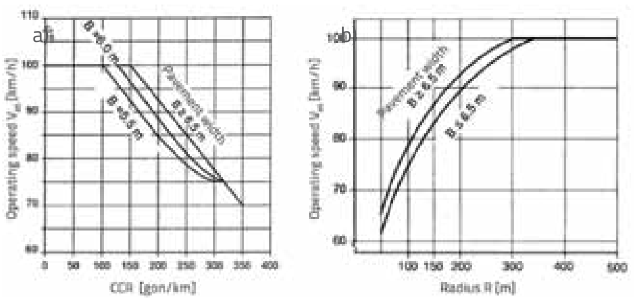

Figure 5. Determination of operating speed [13]: a) for consistent horizontal alignments; b) for existing horizontal alignments

In Italy and Switzerland, the official approach for achieving alignment consistency [19] implies drawing/development of the operating speed profile. According this method, operating speeds are obtained by equation (1) and in fact represent so called design speed V_p rather than the 85 % speed. The speed profile is plotted under assumption that decelerations and accelerations occur outside of curves, with the accepted rate of 0.8 m/sec². An example of speed profile is given in Figure 6.

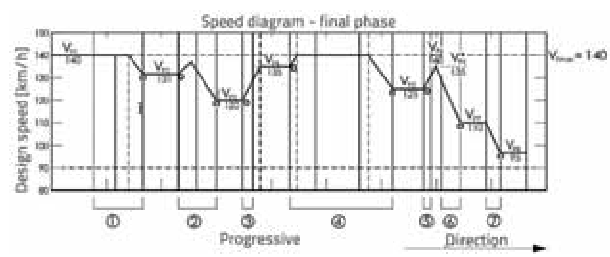

Figure 6. Example of speed profile [11]

Once a speed diagram is developed, the speed consistency has to be verified. Italian and Swiss guidelines apply the following consistency criteria for roads with V_p<80 km/h:

- The difference in operating speed between homogeneous sections with flat curves and sections with sharper curves must be less than 5 km/h,
- The design speed difference between two successive curves must never be greater than 20 km/h and, if possible, it should not exceed 10 km/h.

The deficiency of speed profiles used in Italy and Switzerland lies in the fact that they use theoretical values of speed calculated using the equation (1), rather than the 85 % speed values that are significantly greater. To remedy this deficiency, studies [21] and [22] were conducted over the last few years in Italy to further analyse and evaluate the operating speed and consistency of road elements.

In Austria [20], the operating speed is defined as the 85% vehicle speed in free flow conditions. It is determined as a function of the horizontal curve radius (Table 2.), or longitudinal grade (smaller value is adopted). If the value obtained in this way is less than the maximum speed specified for a particular road category, then the maximum speed is adopted as an acceptable operating speed. Thus, the actual 85% speed is in fact underestimated.

R [m]	50	80	130	200	300	400	500	600	800
V_{85} [km/h]	50	60	70	80	90	100	110	120	130

Table 2. Estimation of operating speed V_{85} according to Austrian guidelines

Austrian guidelines do not provide any quantitative criteria for consistency evaluation. It is only mentioned that the highway alignment should be selected in such a way that there are no "abrupt" changes to the profile.

3.2.1. Croatia

Croatian guidelines for road design [23] were made on the basis of German guidelines dating from the years 1973 and 1984. They define following terms:

1. Design speed is the maximum speed for which safety is guaranteed along the entire road section,
2. Project speed is the maximum expected speed in free flow conditions that can be achieved with sufficient safety on a particular part of the road segment depending on its horizontal and vertical characteristics.

Project speed is determined by equation (1) as a function of the curve radius (as in Switzerland and Italy), or the largest longitudinal grade (smaller value is adopted), Table 3.

Table 3. Determination of project speed with respect to horizontal curve radii

Vr [km/h]	30	40	50	60	70	80	90	100	110	120	130
R [m]	25	45	75	120	175	250	350	450	600	750	850

Consistency criteria are similar to those used in other European countries, namely:

- The difference between the project speed and design speed within a section should be less than 20 km/h,
- The maximum difference in the project speed within a section should be less than 15 km/h.

The diagram of the adjacent curve radii based on the German guidelines (1973.) is used for evaluation of the allowable speed difference between the elements. The guidelines also define the values of the minimum curve radius after long independent tangents.

The above review of guidelines used in European countries reveals that all guidelines contain similar criteria for the evaluation of speed consistency. The main difference is in the way in which the operating speed is defined and determined. German guidelines give equation for operating speed on a particular element, which is used for checking consistency of existing roads. They also give equation for estimation of the 85 % speed on a homogeneous road section, which is used for the design of new roads.

Italian, Croatian and Swiss guidelines compute the project speed according to equation (1), which ignores the fact that the operating speeds are higher.

3.3. Superelevation and side friction factor in mild curves

Unlike guidelines used in the United States of America, those used in European countries apply only one method for the distribution of superelevation and side friction: the superelevation and side friction linearly decrease as the curve radius increases. It would be ideal if drivers were to drive at constant (design) speed, which is obviously impossible. As guidelines used in European countries limit the size of elements according to consistency criteria, this method of distribution would seem as a logical solution. The problem occurs with guidelines of those countries (Croatia, Italy, Switzerland) that have not developed equation for estimation of the 85 % speed, but rather calculate speed according to equation (1) as a function of curvature radius and the values of f_{Rd} and $\varepsilon_{max.}$ This speed is lower than the operating speed, which can result in selection of inappropriate superelevation values, and in considerable overstepping of design values. An additional problem in Croatian guidelines is related to the design of 3rd, 4th and 5th category roads because the project speed is taken to be equal to the design speed.

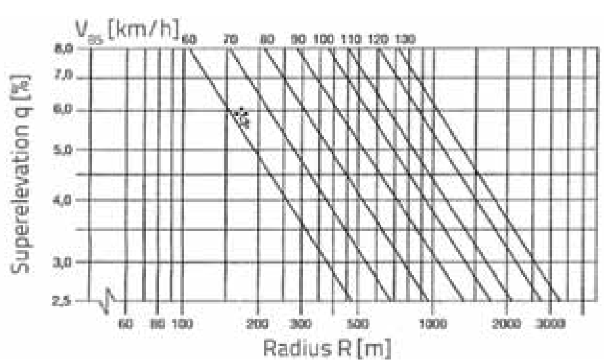

Figure 7. Radius-superelevation relationship [13]

Unlike most other European countries, German guidelines apply superelevation rate of up to 8 % in sharp curves in order to reduce the resulting side friction value (i.e. they take into account that $V_{85}>V_d$). In this way, the design friction values can not be greatly exceeded. The logarithmic graph of superelevation with respect to R and V_{85}, as used in German guidelines [13], is shown in Figure 7.

4. Consequences of the use of different methodologies on driving safety in curves

A review of existing guidelines has revealed various deficiencies in the design of horizontal alignment. In the USA the biggest problem is the lack of quantitative criteria for limiting the value of curve radius and tangents lengths, which often leads to road design involving inconsistent elements. Yet another problem is that the most important road parameters (superelevation, visibility) are determined based on the design speed that is considerably lower than the operating speed, which may be the cause of many accidents. This problem is partly compensated by parabolic distribution of superelevation in mild curves, which indirectly takes into account the fact that operating speeds are different from design speeds.

In almost all European countries, the guidelines define the project speed as a criterion for determining superelevation and visibility restrictions. They also provide criteria for speed difference between adjacent elements of the alignment. However, there is a significant difference in the manner in which the project speed is determined. In Germany, the project speed is the operating speed obtained by field survey, while in other European countries (Croatia, Switzerland, Italy) the project speed is a theoretical value obtained from equation (1). This speed is always lower than the operating speed.

An example of a 3rd category rural road (according to Croatian guidelines) is used to present consequences of applying different guidelines, in terms of determining the distribution of superelevation and side friction. A curve with the radius of R = 300 m, and 70 km/h design speed is analyzed.

According to Croatian guidelines, the superelevation is calculated with respect to V_p. For the 3rd road category, the design speed is taken as the project speed (70 km/h), resulting in the superelevation of 4.8 %. In case of the 1st or 2nd category road, the project speed V_r would be 85 km/h. This speed is much more realistic than the speed of 70 km/h that is used for the 3rd road category, i.e. it is closer to the operating speed of most drivers in a curve with the radius of 300 m (about 100 km/h, Figure 1), and it is also compliant with consistency criteria. The superelevation value according to USA guidelines is calculated with respect to V_d, and it amounts to 6.7 %. According to German guidelines (Figure 5.b), the operating speed is 98 km/h for a 300 m radius (road width:

Table 4. Comparison of Croatian [23], USA [14] and German [13] guidelines for R=300 m, V_p=70 km/h

Guidelines	V_p [km/h]	V_{mj} [km/h]	R [m]	q [%]	85 [km/h]				98 [km/h]		
					q	f_R	f_{Rdop}	$f_R - f_{Rdop}$	f_R	f_{Rdop}	$f_R - f_{Rdop}$
Croatia	70	70 (V_r=V_p)	300	4,8	6,2	0,142	0,125	0,017	0,204	0,108	0,100
USA (method 5)	70	70 (V_p)	300	6,7	6,7	0,123	0,135	-0,012	0,185	0,115	0,070
Germany	70	98 (V_{85})	300	8,0	6,1	0,110	0,125	-0,015	0,72	0108	0,064

up to 6 m) and the superelevation is 8 %. This speed exceeds the permissible difference between V_{85} and V_d (20 km/h according to Table 1). Also, the curve radius of less than 380 m should not be applied for the operating speed of 98 km/h [13]. Therefore, according to German guidelines, such large radii should not be used for roads with V_d = 70 km/h. But this would nevertheless be allowed according to Croatian and USA guidelines. This comparison was made for the radius of 300 m in order to emphasize the shortcomings of these guidelines. Speeds used for calculating reference superelevations are shown in Table 4. The resulting side friction values and design side friction values according the Croatian, German and USA guidelines, are also presented.

The results clearly show that drivers in curves with different superelevation values (in the order of 4.8, 6.7 and 8 %) feel different side friction. Assuming that the operating speed is 85 km/h for a 3rd category road, the application of Croatian guidelines would result in overstepping the maximum allowable design side friction factor f_{Rd} by 0.017 (column 9), i.e. by 14 %. Superelevation rates calculated according to the USA and German guidelines for the speed of 85 km/h would not result in the overstepping of design side friction values.
The comparison of resulting side friction values for 98 km/h is shown in the last three columns (10, 11 and 12). For this speed, all guidelines would result in side friction values that are in excess of design values. Croatian guidelines would point to the side friction factor that is 90 % (0.100) higher than the design value. This value is close to the critical skid side friction which is about 2 times higher than the design value. According to German and USA guidelines, the design value is exceeded by 60 %, and so some reserve would still remain until the critical skid value. It can be seen that the difference between f_R and f_{Rd} values of side friction does not meet the third consistency criterion. It exceeds the design value by 0.04 (Table 1), which could have been expected because neither the first criterion has been met.

In case that project speed for the 3rd category roads were to be determined in the same way as for the higher road categories, according to Table 3., then the V_p would have been 85 km/h instead of 70 km/h, and the superelevation rate would have been 7 %. Such superelevation corresponds better to actual speeds on the roads, and the side friction would exceed much less the design side friction values (about 70 %).
It can be seen from this example that there is a realistic need to estimate the 85 % speed and speed profile, and this not only to harmonize adjacent road elements in terms of consistency, but also to be able to select an optimum superelevation distribution method with respect to actual driving speeds in curves.

The fact that the operating speed is not taken into account in the road design process is partly compensated by the USA method of superelevation distribution, while the application of Croatian guidelines (for the lower road categories) leads to significant overstepping of design values of f_{Rd}, which could result in traffic accidents. German guidelines are considered to be the most appropriate ones in terms of speed and side friction consistency.

5. Conclusion

It can be seen from this overview that only the USA have not incorporated the criteria for ensuring consistency of road section elements. All alignment elements are determined according to the design speed. Using the design speed rather than the operating speed is partly compensated by applying parabolic distribution of superelevation and side friction in curves. This indirectly takes into account the fact that drivers drive above the design speed in case of free flow conditions. An additional problem in the USA guidelines is that several maximum superelevation values are defined, depending on traffic and weather conditions. The result is that different superelevations are applied in curves with similar radii on roads belonging to the same category. Therefore, the resulting side friction for the same speeds is different, which can cause an inadequate driver reaction (and accidents).

Guidelines applied in European countries contain very similar criteria for determining the speed consistency between adjacent elements of the alignment, and for relationship between the project speed and design speed.

The main difference between guidelines applied in various European countries is that some of them use the estimated 85 % (operating) speed for the design speed determination, while other guidelines take into account the project speed, which is a theoretical value calculated according to equation (1). Because the project speed is lower than the operating speed, it results in superelevations that are less than optimal for a comfortable ride. The biggest shortcoming of Croatian guidelines lies in the fact that the superelevation and visibility calculations for the 3rd, 4th and 5th category roads are based on the design speed rather than on the project speed. This results in superelevation values that are less than optimal for a safe and comfortable ride. A review of recently published papers shows that numerous studies focus on driver behaviour (acceleration, deceleration, speed) as related to road characteristics and environment, the objective being to improve national guidelines with respect to consistency in road design. This activity is expected to result primarily in safer, more comfortable, and less costly transport.

In Croatia, the priority in research should be given to the determination of dependence between the operating speed and the traffic, road, and environment-related properties, and to the use of operating speed in the calculation of superelevation and visibility for all road categories.

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