DEPENDENCE OF CARRIAGEWAY CROSSFALL ON OPERATING SPEED

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Abstract: This paper describes a rational approach to improve the existing guidelines for road design in the regions of Slovenia, Croatia, Bosnia and Herzegovina, and Serbia in order to determine the carriageway crossfall in curves. In these guidelines there are certain shortcomings in determination of crosfall in comparison to some other European countries guidelines. During the last decades, worldwide and in Europe specifically, significant studies have been conducted on the issue of the operating speed and its implementation into the design process. Most European countries have been implementing this concept. The new German guidelines went a step further and introduced a new concept of a self-explaining class road. Using the results of research carried out in Croatia, this work focuses only on a determination of the carriageway crossfall based on operating speed, separately observing new and existing roads. Whereas the new road segments require implementing the principle of a consistent route, an existing road network can be safely improved only by introducing the criteria of the determination of crossfall in curves based on the operating speed.

Keywords: carriageway crossfall; operating speed; new segment; existing road network

POPREČNI NAGIB KOLNIKA U FUNKCIJI OPERATIVNIH BRZINA

Sažetak: U radu se objašnjava mogući koncept racionalnog pristupa poboljšanju postojećih pravilnika za projektiranje cesta u regiji (Slovenija, Hrvatska, Bosna i Hercegovina, Srbija) s gledišta određivanja poprečnog nagiba kolnika u krivinama. Analizirani su nedostatci u usporedbi s nekim europskim pravilnicima. Naime, u posljednjim desetljećima u svijetu i Europi napravljena su važna istraživanja na temu operativnih brzina i njihovog uvođenja u postupak projektiranja. U većinu pravilnika implementiran je taj koncept. U novim njemačkim smjernicama otišlo se korak dalje, odnosno uveden je novi koncept „samoobjašnjavajućih„ (*self-explaining*) klasa cesta. Koristeći se i rezultatima istraživanja provedenih u Hrvatskoj, u radu se ograničilo samo na poprečni nagib kolnika u funkciji operativne brzine. Odvojeno se promatraju nove dionice koje zahtijevaju i uvođenje principa konzistentnosti trase, od dionica postojeće mreže cesta koje je moguće sigurnosno poboljšati samo uvođenjem kriterija određivanja poprečnog nagiba u krivinama temeljem operativne brzine.

Ključne riječi: poprečni nagib; operativna brzina; nova dionica; postojeća mreža

1 INTRODUCTION

In the road network two-lane rural roads have the highest percentage. Unlike motorways that have a clearly defined function and safety rules and criteria during the planning, design, construction, and exploitation phases, two-lane roads have no unambiguous definitions of the functionality and design solutions, and in terms of traffic safety, the problems are more difficult.

Numerous studies have shown that approximately 50% of traffic accidents occur owing to an inadequate design of the horizontal alignment [1-3]. Many guidelines [4-6], do not adequately define how to obtain a consistent road segment. Road segment consistency provides safe driving conditions at the desired speed across the route, whereas inconsistency is reflected when drivers need to slow down for a safe connection to the next road element, thus increasing the likelihood of an accident [7].

One of the key steps to achieving consistency is the implementation of the operating speed in the design process. Many studies [8-11] have shown that the operating speeds along curves with a radius larger than the minimum are greater than the design speeds. This problem is most noticeable in a sharp curve following the flat curve where the operating speed is greater than the design speed and the radial friction coefficient (f_R) between the tires and the pavement significantly exceeds the allowed values. The subject of this article is an analysis of the carriageway crossfall as a function of the speed, which is defined differently in different guidelines [4-6, 12] (basic, computational, project, design, and predictable speeds). These speeds from the guidelines are referred as design speeds below, while speed of 85% most faster driver will be defined as operating speed (V_{85}).

Studies conducted in Croatia [8, 13, 14] also confirm the fact that operating speeds are greater than the design speed. In this particular case (Figure 1a), for a road section with a design speed of 60 km/h, the limit value of the radius, where the operating and design speeds became equal, is approximately 300 m [13]. The differences between the operating and design speeds results in an exceedance of the allowed f_R values (Figure 1b). The values of the activated radial friction coefficients in all curves exceed twice the permissible values and are significantly higher than the maximum values.

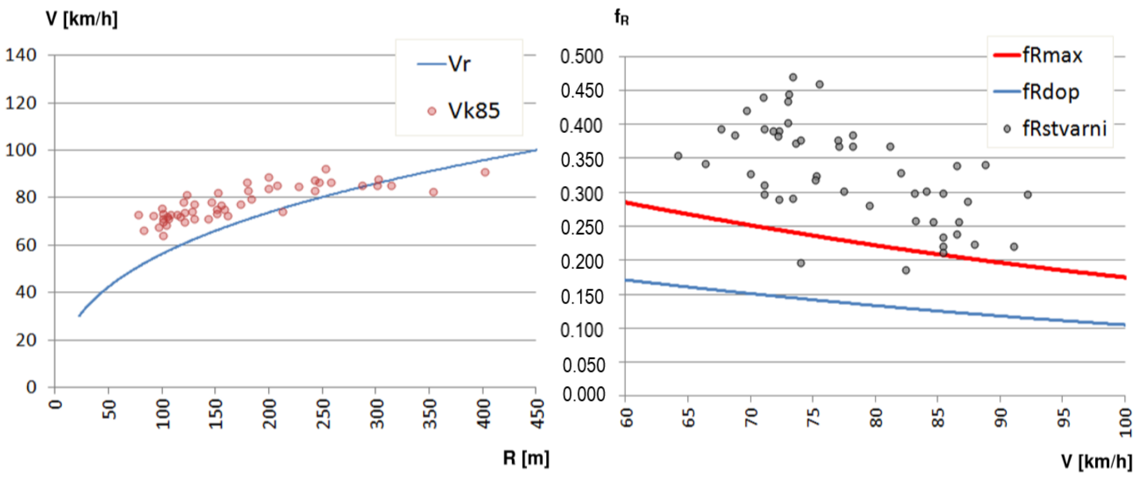

Figure 1 a) Relationship between design (V_r) and operating (V_{k85}) speeds along the horizontal curves; b) relationship between the real radial friction coefficients ($f_{Rstvarna}$) and the maximum (f_{Rmax}) and allowed (f_{Rdop}) coefficients for the operating speeds [13]

Furthermore, for radii greater than the minimum, it is necessary to determine the most favorable ratio of the crossfall and radial friction coefficient according to the operating speed. In the guidelines of different countries [4-6, 12] there are considerable differences in the choice of speed according to which the crossfall and f_R values are calculated. Some road design guidelines, such as for old German [15] and Australian [16] roads, recognize this problem by using the 85th percentile operating speed obtained through a field survey. The operating speed is defined as the speed below which 85% of the vehicles actually drive under free flow conditions. However, some other guidelines for a road design [4–6] use the theoretical value of the speed, herein called the design speed, rather than the 85th percentile operating speed. For example, the Croatian guidelines define project (V_p) and design (V_r) speeds. The design speed is defined as the maximum expected speed under 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. This is was determined from the basic equation of the vehicle stability along horizontal curves, as a function of the applied curve radius or largest applied longitudinal grade.

The Croatian guidelines also define the design speed as a criterion for determining the super-elevation and stopping sight distance and provide consistency criteria in terms of the design and project speed consistency and the consistency of the design speeds within a single road section. The problem is that this design speed (which is a theoretical value) is less than operating speed for radii of less than 300 m, as mentioned earlier.

The choice of unrealistically low values of these speeds results in the application of insufficient crossfalls in the curves, leading to a greater friction resistance of the vehicle in order to keep the circular motion than the driver expects. This can lead to driver insecurity and braking, thus triggering the friction component in the longitudinal direction, which reduces the available radial friction resistance and increases the possibility of a single vehicle run-off-road accident. Therefore, a good road project, apart from the consistency of the alignments, must match the crossfall values and engaged radial friction resistance with real speeds.

This article analyzes only the application of the crossfall in curves of radii larger than the minimum using the results of the above-mentioned research and guidelines of certain countries in the region of Slovenia, Croatia, Bosnia and Herzegovina, and Serbia, as well as in Europe to compare the disadvantages of the existing guidelines in the region. The conclusions provide a way to improve such guidelines.

2 REVIEW AND ANALYSIS OF THE GUIDELINES

In this paper, the application of the carriageway crossfall according to two groups of guidelines is analyzed. The first group has the criterion of an optimal ratio of the crossfall and radial friction coefficient in such a way that they retain the maximum value of the crossfall to a particular radius, for which surveys have shown [13] that the design and operating speeds reach almost the same values (Figure 1). German [17], Austrian [18], and Serbian [12] guidelines were selected. The second group of cross fall guidelines is determined based on the radial stability conditions of a vehicle based on the design speeds without considering the operating speed. Bosnian and Herzegovinian [4], Croatian [5], and Slovenian [6] guidelines were selected from this group.

2.1 First group of guidelines

The German guidelines were made separately for the design of the motorways (RAA), rural roads (RAL) [17], and urban roads (RAST). The graph in Figure 2 refers to rural roads divided into four design classes (EKL 1 to EKL 4) and a speed range of 110 to 70 km/h. The continuous line represents free road segments, whereas the dashed line is for zones of intersections. The change in the crossfall from a maximum of 7% to a minimum of 2.5% for all mentioned road design classes and their speeds range from a radius of 350 to 1,000 m. The new German guidelines introduced a new approach, which are briefly described at the end of this paper because their concept is not directly related to the subject of this article.

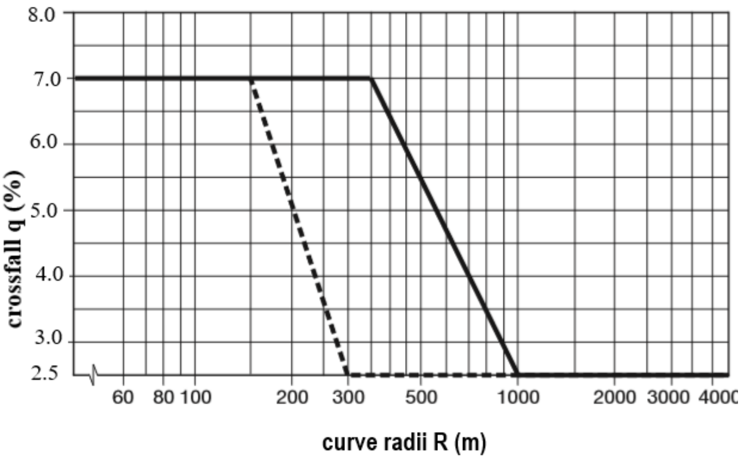

Figure 2 Crossfall as a function of curve radius in RAL [17]

The Austrian guidelines (Table 1) divide the roads into federal roads with maximum speeds of greater than 100 km/h and rural roads with a maximum speed of ≤ 100 km/h in terms of the maximum crossfall application. These guidelines also retain a maximum value of 7% for a 400 m radius, which can be reduced to a minimum of 5% owing to the justified local conditions.

Table 1 Maximum crossfall in the curve - Austrian guidelines [18]

Speed V > 100 km/h (Motorways and Expressways A and S)	**R** [m]	≤ 800	1000	1200	1400	1600	1800	≥2000	
	q_{max} [%]	6	5	4.5	4	3.5	3	2.5	
Speed V < 100 km/h (Other classes of Rural roads)	**R** [m]	≤ 400	500	600	700	800	900	1000	≥1200
	q_{max} [%]	7	5.5	4.5	4	3.5	3.5	3	2.5

The Serbian guidelines [12] (similar to the Austrian guidelines) separate the motorway from the other rural roads by providing separate diagrams for determining the crossfall of the carriageway in the curves by setting the boundary difference across a lane width of 3.5 m (Figure 3).

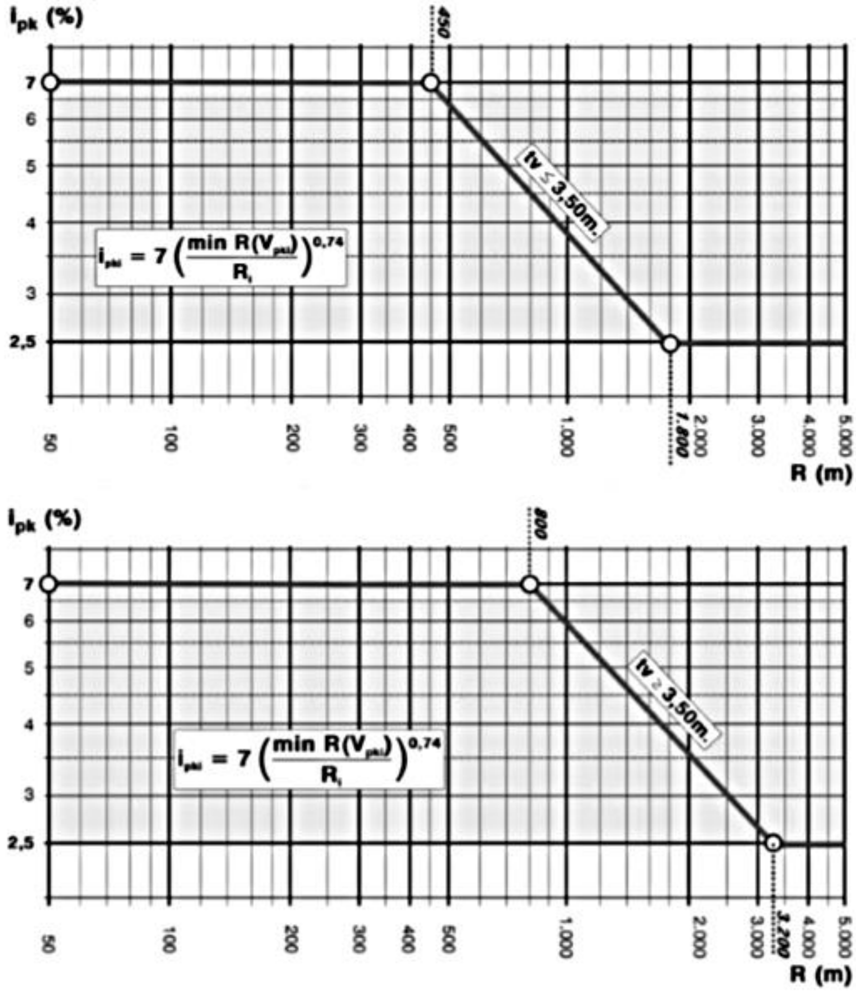

Figure 3 (top) Carriageway crossfall i_{pk} for lane widths of up to 3.5 m, (bottom) carriageway crossfall i_{pk} for lane widths exceeding 3.5 m [12]

2.2 Second group of guidelines

As shown in Table 2, the Slovenian guidelines [6] are based on determining the crossfall for the design speed. For example, for a design speed of 60 km/h, a minimum slope of 2.5% is determined for a radius of 350 m, and from the above-mentioned research, it is apparent that the operating speeds may be greater than 80 km/h.

Table 2 Crossfall as a function of curve radius – Slovenian guidelines [6]

Design speed	Minimum radii for different crossfalls (m) Crossfall									
	2,5%	3,0%	3,5%	4,0%	4,5%	5,0%	5,5%	6,0%	6,5%	7,0%
30 km/h	70	60	50	45	40	35	33	30	27	25
40 km/h	125	110	90	80	70	65	60	50	47	45
50 km/h	200	175	150	127	120	110	98	90	77	75
60 km/h	350	280	240	210	180	165	150	140	127	125
70 km/h	500	420	360	320	280	250	230	210	190	175
80 km/h	700	580	500	420	390	350	320	290	270	250
90 km/h	1000	800	700	620	550	490	450	400	370	350
100 km/h	1250	1050	920	780	700	640	580	550	480	450
110 km/h	1700	1400	1200	1050	950	850	780	700	650	600
120 km/h	2000	1750	1500	1375	1175	1050	960	900	840	750
130 km/h	3000	2100	1800	1550	1400	1250	1150	1050	950	900

The Croatian guidelines [5] determine the carriageway crossfall along a curve based on the design (class 1 and 2) or project (class 3, 4, 5) speed according to the graph in Figure 4, and have higher (slightly safer) criteria than the Slovenian guidelines because, for the design speed of 60 km/h, the minimum crossfall is for a radius of greater than 520 m. The difference between the design and operating speeds was described earlier.

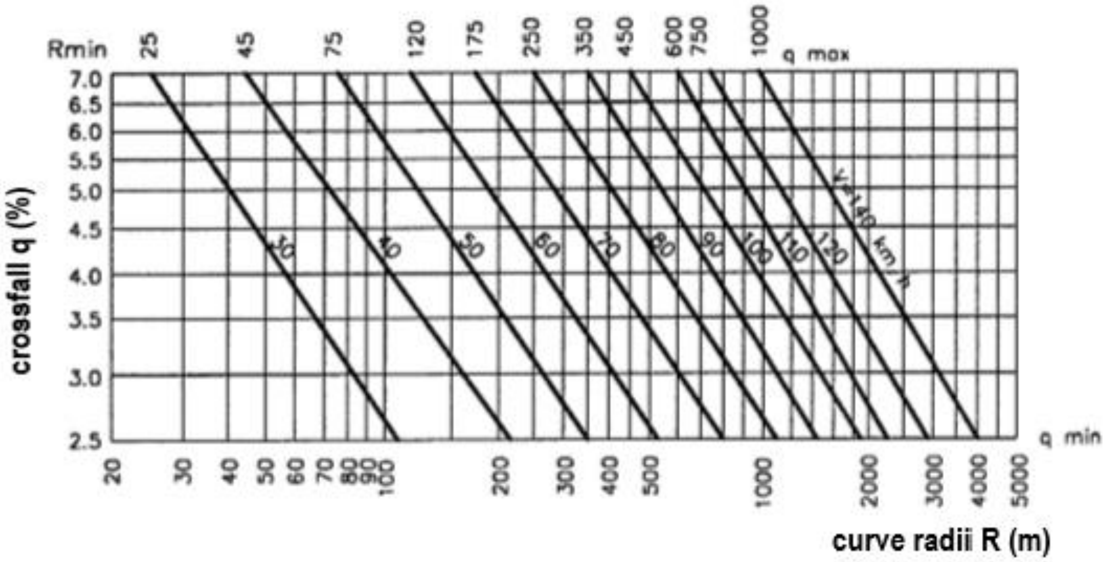

Figure 4 Crossfall as a function of curve radius for design speed Vr – Croatian guidelines [5]

The Bosnian–Herzegovinian guidelines [4] have a number of fundamental settings that need to be corrected. One of them is the division of roads into technical groups A, B, C, and D, which are the foundation for the design. For the same design speed, completely different elements of the road geometry can be obtained. As an example, Figures 5 and 6 show graphs for determining the crossfall for technical groups A and B. If a road with a speed of 60 km/h is illogically (according to these guidelines) classified as technical group A, the minimum crossfall can be applied for a radius of greater than 500 m (a similar situation as in the Croatian guidelines). If the road is classified into technical group B according to these guidelines, the minimum radius for q = 7% is 100 m, and for a radius of greater than 180 m, the crossfall is 2.5%. This result is quite illogical and does not warrant further comment. In practical terms, in the B & H guidelines, only a technical group A diagram is applicable.

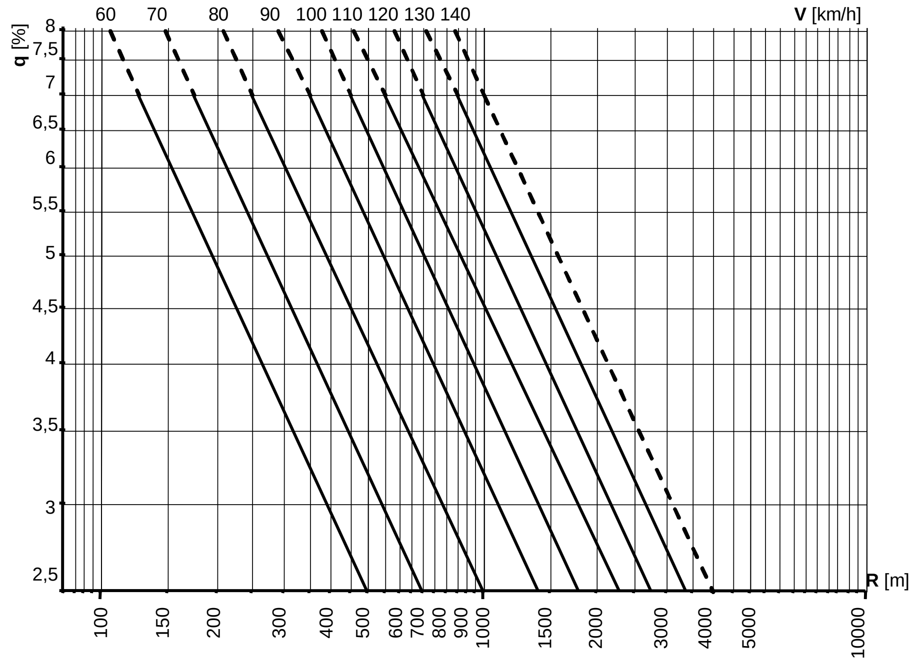

Figure 5 Crossfall for technical group A [4]

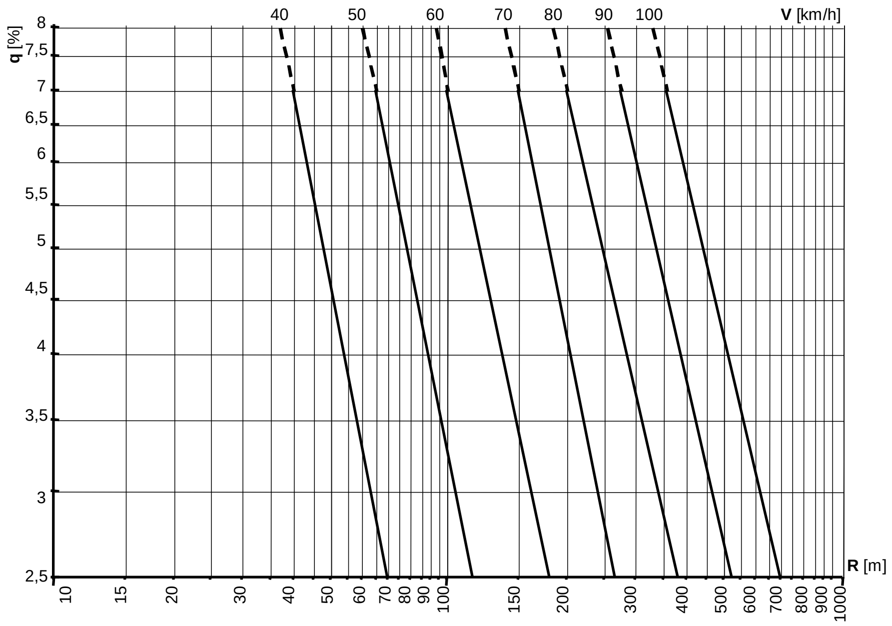

Figure 6 Crossfall for technical group B [4]

3 DISCUSSION

Based on the chapter above, the following can be underlined:

- The first group of guidelines has a unique rule for determining the crossfall for all rural roads (excluding motorways): German guidelines [17] for all classes (EKL1 to EKL4), Austrian guidelines [18] for all road speeds of up to 100 km/h, and Serbian guidelines [12] for all roads with lane widths of up to 3.5 m (which is indirectly valid for speeds of up to 100 km/h). Thus, they all retain the maximum values of the crossfall to certain radius values (350, 400, and 450 m) simply for the operating speed.

- The second group of guidelines for different speeds (30 to 130 km/h) gives different crossfalls. They also define the speeds differently (project, design, and predictability), herein called the design speed (for simplicity), but none are the operating speed, which is also noticeable compared to the first group diagrams.

For a graphical drawing of all guidelines together (Figures 7 and 8), speeds of 80 and 60 km/h and lower-class roads were selected. In the case of the Croatian guidelines [5], road classes 3, 4, and 5 were selected for which the project speed can be determined to be up to 80 km/h (depending on the degree of restriction). This speed is basic for a crossfall determination.

Figure 7 shows a comparison of the crossfall determination for a design speed of 80 km/h according to the previously analyzed guidelines. From the graph, it is apparent that the German guidelines [17] apply a maximum crossfall of 7% for all classes of rural roads and for all radii below 350 m. The Austrian guidelines [18], which are similar to the German guidelines for speeds ≤ 100 km/h, apply a maximum 7% crossfall for radii ≤ 400 m. The Serbian guidelines [18] have the strongest criteria in that the crossfall changes from a maximum of 7% for radii ≤ 450 m to a minimum of 2.5% for only radii ≥ 1,800 m at a lane width of ≤ 3.5 m, which again indicates all rural roads except a motorway, or speeds of up to 100 km/h.

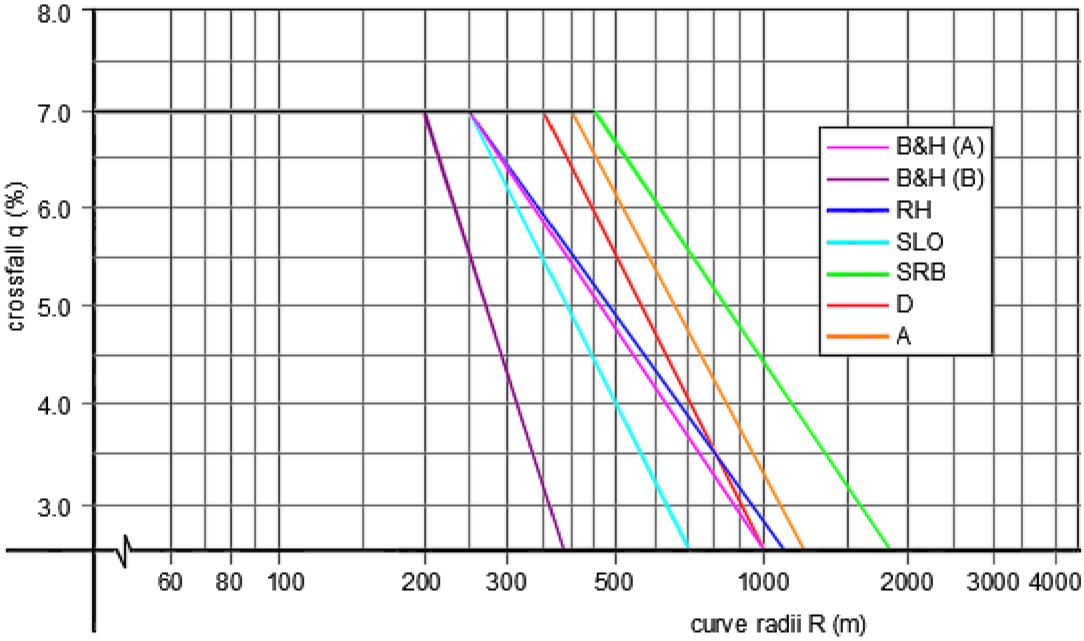

Figure 7 Crossfall according to the different guidelines for speeds of 80 km/h

Other guidelines such as B&H [4], HR [5], and SLO [6] apply a crossfall directly to the design speed. Therefore, they do not take into account the introductory fact that all studies [8-11, 13] have shown that the operating speed are greater than the design, or the basic assumption regarding the radial stability of the vehicle in curves with radii greater than the minimum. For the conditions of reduced adhesion (which is not so rare), the problem is even more pronounced. By comparing these three guidelines, there are significant differences in the application of the minimum crossfall of 2.5% in the curves. For example, keeping the design speed of 80 km/h in the HR guidelines [5] allows for ≥ 1100 m, whereas SLO [6] allows for ≥ 700 m, and BH [4] provides completely different results depending on the division of the roads according to Technical Groups A, B, and C. The only aspect that makes sense from the perspective of the crossfall determination is technical group A, in which q_{min} is applied for R ≥ 1,000 m. The graph also shows the crossfall change for technical group B where applying a minimum crossfall for radii ≥ 400 m is allowed.

In recent decades, numerous operating speed models have been developed [11] for use in the design phases to determine the geometrical elements of the alignment by emphasizing the need to define additional criteria in the guidelines to obtain a consistent segment as the final result.

Analogous crossfall ratios according to different guidelines have also been presented for a speed of 60 km/h (Figure 8), where the difference in the ratio between the crossfall and radius is even more pronounced.

For example, a section of an existing road (class 3, design speed = project speed = 60 km/h such as with the section upon which the measurements were conducted, as shown in Figure 1) was selected for reconstruction and improved safety. The German guidelines [17] should be representative of the first group; and the Croatian [5] guidelines, representative of the second group. From Figure 8, it can be seen that for R = 350 m, according to the Croatian guidelines, the crossfall is q = 3.7%, and according to the German guidelines, the maximum crossfall is q = 7%.

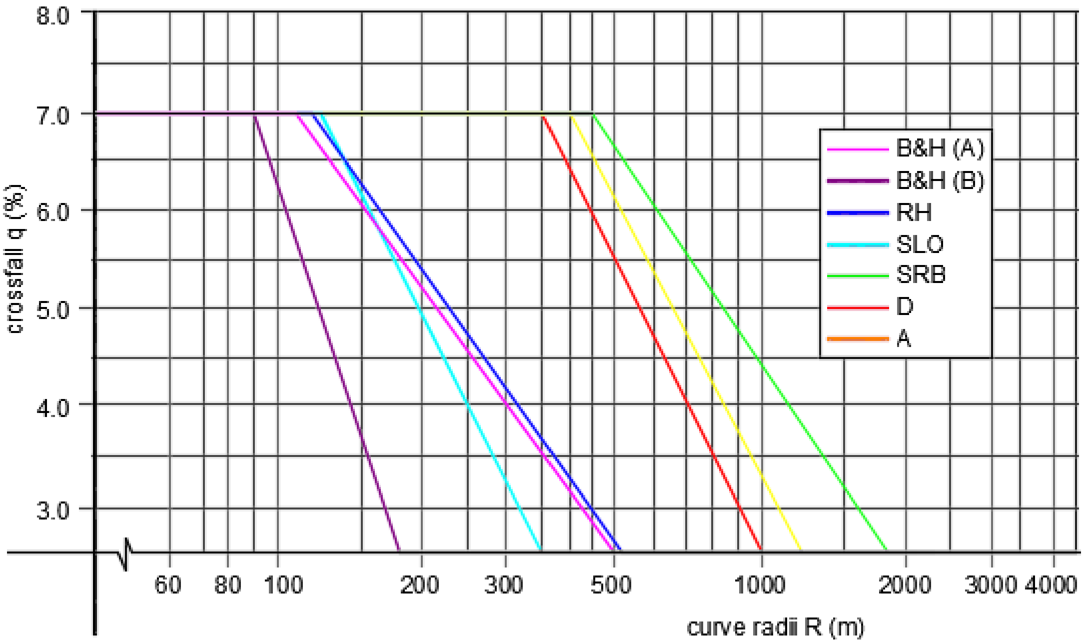

Figure 8 Crossfall according to the different guidelines for speeds of 60 km/h

The different approach adopted in the new German guidelines [17] leaves the concept of operating speeds and introduces the concept of design road classes [19]. As defined in the guidelines, this means the following: The road should be designed in such a way as to offer a very limited number of road types to the road user, and within each type of road, the characteristics should be as uniform as possible. All features together should make the road self-explanatory, which means that the experienced driver knows a typical combination of elements for each type of road and what kind of driving corresponds to the characteristics of a certain type of road. The driver should be able to recognize the type based on the geometric properties and types of intersections. This requires that the design elements within one type of road are extremely similar, and that the elements of different types of road be distinguished as much as possible. As a result, this concept produced four types of rural roads classified into the design class. As previously mentioned, this approach also includes a crossfall application as a function of the operating speed.

4 CONCLUSION

The analysis conducted in this paper shows that the application of a carriageway crossfall (problem/solution) should be considered from two aspects. One aspect is designing new sections of rural roads with speeds of less than 100 km/h, whereas the other is an improvement (increase in safety) of existing two-lane roads (motorways are dealt with separately). When designing new road segments, regardless of which concept is applied (the operating speed or design class of a self-explaining road), the problem of a crossfall determination in the curves is automatically solved.

For an existing road network, it is insufficient to introduce new principles into the guidelines. It is practically impossible to achieve consistency of a route by improving the existing road and can only be achieved with a new section. The solution is to introduce operating speed principles to increase safety on an existing road network. For a determination of the crossfall in curves with radii larger than the minimum, it is clear that the maximum crossfall should be kept to the limit where the values of the design and operating speeds are assumed at almost the same values.

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